Flood Plain Management Services

# Storm Water Management Model (SWMM)

Worcester, Massachusetts

December 1991

US Army Corps of Engineers
New England Division

# STORM WATER MANAGEMENT MODEL

WORCESTER, MASSACHUSETTS

December 1991

Department of The Army
New England Division
Corps of Engineers
Waltham, Massachusetts

## EXECUTIVE SUMMARY

This study was conducted at the request of the City of Worcester, Massachusetts, Department of Public Works under the Corps of Engineers' Flood Plain Management Services (FPMS) program. The FPMS program is authorized under Section 206 of the Flood Control Act of 1960 (PL 86-645). This program allows the Corps to provide planning and technical assistance to states, regional authorities, and communities in matters relating to flooding and flood plain management.

This FPMS investigation utilizes the information from the Storm Water Management Model (SWMM) developed by the Corps under a separate "Work For Others" (WFO) agreement with the City of Worcester. The City of Worcester requested the work to assist in the development of an uncalibrated, nonverified mathematical model of the City's existing storm drain system. This model is designed to allow for simulation of stormwater runoff from the Worcester drainage area for selected storm events. The model was developed to allow routing of rainfall from the overland flow areas (subcatchments) through pipes of the storm drain system to predict the outfall hydrograph.

The purpose of the WFO investigation was to provide assistance to the city in:

- Identifying areas of deficiency in the existing drainage system, and
- Evaluating future expansion of the system.

The outflow hydrographs may be used to aid in urban drainage design for prevention against flooding. It is anticipated that the model will also assist the City in meeting future requirements of the Environmental Protection Agency's (EPA) National Pollutant Discharge Elimination System regulations.

The tasks performed in the FPMS investigation include:

- Selection and development of rainfall hyetographs for historical and design storm events that are used as input for the Storm Water Management Model (SWMM).

- Running the SWMM for the input storms and analyzing the output hydrographs.

- A sensitivity analysis of selected model parameters for a representative area.

- A project report explaining the modeling approach and assumptions, and an analysis of information for each drainage area.

- The identification of potential storm drainage system problems, and recommendations for future work.

Ten major drainage areas were defined within Worcester using topographical maps provided by the city. The outfalls for the drainage network were subsequently identified using the city's storm sewer maps originally produced by Fay, Spoffard, and Thorndike. There are two hundred and six (206) storm drain outfalls which have been identified within the ten major drainage areas. One-hundred and ten outfalls were modeled, or about 53% of the total number. The other 96 outfalls (47% of total) contained either short pipe networks, small diameter pipes (i.e., less than 12") draining a small area, or combined sewers. None of these areas were modeled in this study.

The Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM) is a mathematical model which can simulate synthetic or historic storm events on the basis of rainfall hyetographs and system characterization to predict resulting outflow hydrographs. All aspects of the urban hydrologic cycles are simulated, including surface runoff and transport through a drainage network.

The process of modeling the Worcester storm drainage system consisted of utilizing two major components of the SWMM application. These components are the Runoff Block and the Transport Block. Figure 2 of the main report illustrates the sequence of input, block applications, and output for this model. The Runoff Block forms the source of runoff hydrographs for most other SWMM applications.

The purpose of the Runoff Block is to develop surface runoff hydrographs at desired inlets to the storm drainage pipe network. The input to this block consists of a rainfall hyetograph and hydrologic characterization of the drainage area including area of each catchment, percent imperviousness, and slope. The hydrographs are required as input to the Transport Block which subsequnetly models the stormwater pipe network.

The purpose of the Transport Block is to route the surface runoff hydrographs developed in the Runoff Block through the pipe network to the outfall. This block produces outfall hydrographs and identifies surcharged elements of the pipe network. However, it does not accurately model surcharged conditions in pipes nor does it account for backwater effects or pressure flows which may develop in the pipe network. A more accurate method for modeling the pipe network may be obtained by utilizing the Extended Transport (EXTRAN) Block of SWMM. EXTRAN has the ability to simulate pressure flows and surcharge, however it is not capable of modeling water quality. The Transport Block was specifically chosen by the City of Worcester to be used in this simulation due to its capability for simulating pollutant load routing through the storm drain pipe network.

Each outfall was modeled with individual input files. Where an outfall is tributary to another outfall, the output hydrograph for the tributary area was input to the downstream outfall. At the city's request, a 25 Year rainfall event was used for modeling all of the outfall areas to reflect the city's design storm event for their drainage system. This 25-Year 24-Hour rainfall event was developed from the U.S. Weather

Bureau's Technical Publication Number 40, and was applied to a historic rainfall distribution based on the 31 March 1987 storm event.

A sensitivity analysis was also performed to determine the output's sensitivity to changes in certain parameters. Outfall hydrographs, and surface runoff from the subcatchments were compared for a range of values of a particular parameter.

The sensitivity analysis concluded that minor changes in determining percent imperviousness (i.e., 20% instead of 25%) do not cause significant changes in the output, specifically the outfall hydrographs or surface runoff volumes. However, more significant changes, such as increasing the percent imperviousness from 20% to 40%, or decreasing from 20% to 5% exhibit more pronounced changes in the volume of surface runoff and subsequently the outfall hydrographs. Therefore, it can be concluded that the results obtained from the application of this model are dependent on the accurate selection of percent imperviousness over the entire catchment area for an outfall.

The SWMM is an extremely helpful tool for stormwater management. However, it is only as accurate as the data which is used as input. Due to limitations in the capabilities of the Transport Block, surcharging effects are not as accurately modeled as can be accomplished using the EXTRAN Block of the SWMM. EXTRAN has the ability to simulate pressure flow and surcharge, however it does not have the capabilities to model water quality. The Transport Block was chosen to model water quality constituents and simulate pollutant load routing through the storm drain pipe network.

The model in its present form is uncalibrated and unverified. Steps to accomplish the calibration and verification of this model are required in order to successfully utilize it for more accurately predicting the rainfall runoff process along with producing pollutographs and modeling any combined sewers. Future work should include calibrating and verifying the existing model parameters and output. According to the SWMM manual "... it is essential that local verification/calibration data be available at specific application sites to lend credibility to the predictions of any urban runoff model."

Calibration can be accomplished by first establishing stations so that flows can be measured at pertinent locations during rainfall events. Flow measurement can be accomplished with permanent gaging stations or with portable instruments. Ideally, continuous gaging stations should be established at each outfall location and at several locations within major outfalls such as Area 26 of the Beaver Brook drainage area. However, if manpower and funds are limited, it is desirable to at least gage several rainfall events at various locations to ensure adequate calibration of the SWMM.

Measured pollutant concentrations at the outfalls are also required data for the calibration/verification process. Water quality predictions are not credible without adequate site-specific data for calibration and verification. Therefore, it is essential that water quality field data be obtained before attempting to use this model for pollutant concentration routing through a particular outfall's storm drain system.

Calibrating and verifying the SWMM is essential towards utilizing it as part of a comprehensive stormwater management plan within the City of Worcester. It is also essential for the eventual modeling of water quality constituents and pollutant loadings which may be required under the National Pollutant Discharge Elimination System permitting process.

STORM WATER MANAGEMENT MODEL
WORCESTER, MASSACHUSETTS

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# I. INTRODUCTION

## STUDY AUTHORITY

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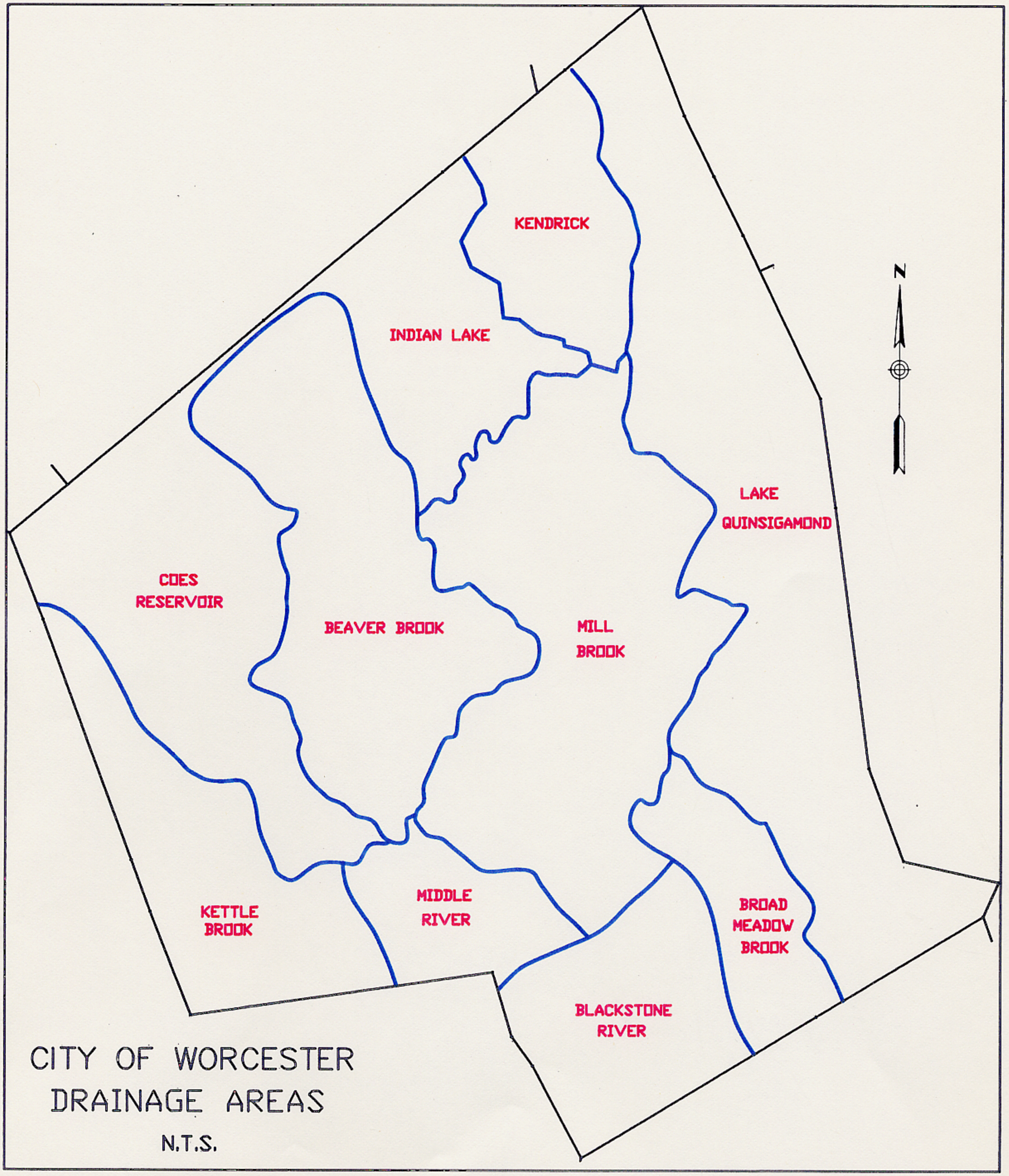
## STUDY PURPOSE AND SCOPE

This FPMS investigation has utilized the information from the Storm Water Management Model (SWMM) developed by the Corps under a separate "Work For Others" (WFO) agreement with the City of Worcester. The City of Worcester requested the work to assist in the development of an uncalibrated, nonverified mathematical model of the City's existing storm drain system. The model is designed to allow for simulation of runoff from the Worcester drainage area for selected storm events. The model was developed to allow routing of rainfall from the overland flow areas (subcatchments) through pipes of the storm drain system to predict the outfall hydrograph.

The purpose of the WFO investigation was to provide assistance in identifying areas of deficiency in the existing system and to evaluate future expansion of the system. The output hydrographs may be used to aid in urban drainage design for prevention against flooding. It is anticipated that the model will also assist the City in meeting future requirements of the Environmental Protection Agency's National Pollutant Discharge Elimination System (NPDES).

The tasks performed in the FPMS investigation include:

- Selection and development of rainfall hyetographs for historical and design storm events that are used as input for the Storm Water Management Model (SWMM).
- Running the SWMM for the input storms and analyzing the output hydrographs.
- A sensitivity analysis of selected model parameters for a representative area.
- A project report explaining the modeling approach and assumptions, an analysis of information for each drainage area.
- The identification of potential storm drainage system problems, and recommendations for future work.


KENDRICK
INDIAN LAKE
LAKE QUINSIGAMOND
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BEAVER BROOK
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MIDDLE RIVER
BROAD MEADOW BROOK
BLACKSTONE RIVER
N
CITY OF WORCESTER
DRAINAGE AREAS
N.T.S.

FIGURE 1

## STUDY AREA

The study area includes the entire city of Worcester, Massachusetts. The city is comprised of approximately 24,600 acres and was divided into 10 drainage areas as shown on Figure 1.

The ten major drainage areas were defined using topographical maps provided by the city. The outfalls for the drainage network were subsequently identified using the city's storm sewer maps originally produced by Fay, Spofford, and Thorndike, Inc.. There are two hundred and six (206) storm drain outfalls which have been identified within the ten major drainage areas. One-hundred and ten outfalls were modeled, or about 53% of the total number. The other 96 outfalls (47% of total) were either short pipe networks, small diameter pipes (i.e., less than 12" diameter) draining a small area, or combined sewers. The areas containing these pipe networks were not included in this study. All of the identified outfalls and the modeled pipe networks are shown on Plates 2 through 12 inclusive.

Table 1 lists the number of outfalls in each drainage area and the corresponding Plate number where the outfalls are shown.

TABLE 1

| Drainage Area | Plate Number | Number of Outfalls | Number of Modeled Outfalls |
|---|---|---|---|
| 1. Beaver Brook | 2 | 22 | 14 |
| 2. Mill Brook | 3 | 64 | 19 |
| 3. Indian Lake | 4 | 18 | 9 |
| 4. Kendrick | 5 | 9 | 8 |
| 5. Lake Quinsigamond | 6 & 7 | 33 | 20 |
| 6. Blackstone | 8 | 6 | 5 |
| 7. Middle River | 9 | 7 | 7 |
| 8. Kettle Brook | 10 | 12 | 9 |
| 9. Coes Reservoir | 11 | 31 | 16 |
| 10. Broad Meadow Brook | 12 | 4 | 3 |
| | | 206 | 110 |

Note: During the collection and aggregation of pipe data, certain outfall areas were found to have actually two outfall pipes. In these instances, the actual outfall pipes for the same area were given different identification numbers within the computer model (i.e., 1000 and 1002).

Table 2 summarizes the information for each major drainage area. It includes the acreage of each modeled outfall area and the sizes of modeled pipes. Refer to Figure 1 for the location of each drainage area within the city.

# TABLE 2

BEAVER BROOK

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 13 | 91.50 | 12", 30" | 30" |
| 14 | 85.20 | 12", 18", 30" | 30" |
| 25 | 55.50 | 15", 20",24", 27" | 20" |
| 26 | 1008.80 | 28", 42", 63", 78", 84" | 78" |
| 40 | 96.10 | 20", 24", 36", 42" | 42" |
| 45 | 277.40 | 60", 54", 48", 42", 36", 33" 70"x70" | 60" |
| 46 | 49.90 | 15", 12" | 15" |
| 54 | 38.80 | 18", 15" | 18" |
| 55 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 56 | 406.10 | 27"x40", 24"x36", 36"x54", 40"x60", 43.5"x45", 30"x45", 48", 45", 50"x75", 48"x72", 34"x51", 44"x66", 30" | 48" |
| 58 | 127.60 | 33"x48", 24"x36", 39" | 33"x48" |
| 59 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 60 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 61 | DNM | COMBINED | |
| 71 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 72 | 91.60 | 16"x24", 20"x30", 22"x33", 30", 24"x36" | 30" |
| 73 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 199 | 8.00 | 24", 20", 18" | 18" |
| 200 | 54.00 | 24", 20", 12", 10" | 24" |
| 201 | 44.40 | 30", 20" | 30" |
| 202 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 203 | DNM | SMALL PIPES OR DRAINAGE AREA | |

TOTAL MODELED AREA 2434.9

NOTE: DNM - Did Not Model

## TABLE 2 (cont.)

BLACKSTONE

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 90 | 103.60 | 20", 24", 16"X24" | 24" |
| 91 | 67.00 | 15", 24", 30", 42" | 30" |
| 92 | 109.73 | 36", 30", 28", 24", 18" | 24" |
| 93 | 132.50 | 36", 30", 24", 21", 18", 15" | 30" |
| 94 | 126.10 | 18", 30", 36", 42" | 42" |
| 95 | DNM | SMALL PIPES OR DRAINAGE AREA | |

TOTAL MODELED AREA 538.93

BROAD MEADOW BROOK

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 96 | 428.30 | 18", 20", 24", 27", 28", 30", 33", 39", 42", 45", 54", 60" | 60" |
| 97 | 36.70 | 18", 21", 24", 30" | 24" |
| 98 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 99 | 18.40 | 15", 18", 24" | 18" |

TOTAL MODELED AREA 483.4

NOTE: DNM - Did Not Model

COES RESERVOIR

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 27 | 171.10 | 15", 24", 30", 36",<br>42", 48", 72", 4' X 6' | 72" |
| 28 | 39.60 | 16", 21", 24" | 16" |
| 29 | 35.10 | 15", 18", 20", 24" | 24" |
| 30 | 82.50 | 21", 30" | 30" |
| 31 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 32 | 178.80 | 18", 20", 24",<br>30", 36", 42" | 42" |
| 33 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 34 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 35 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 36 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 37 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 38 | 118.40 | 21", 20", 24",<br>32", 36", 48" | 48" |
| 39 | 202.50 | 18", 20", 24", 30",<br>32", 36", 42" | 36" |
| 41 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 42 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 43 | 45.50 | 20", 24", 27" | 27" |
| 44 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 47 | 21.30 | 15", 18", 24" | 24" |
| 48 | 16.40 | 18", 24" | 24" |
| 49 | 34.50 | 18", 24", 30" | 18" |
| 50 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 51 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 52 | 27.00 | 24" | 24" |
| 53 | 94.74 | (1000) — 24"<br>(1002) — 18", 30" | 24"<br>30" |
| 62 | 9.70 | 18", 21" | 21" |
| 66 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 67 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 68 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 69 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 70 | 70.90 | 15", 18", 24", 18"x27" | 18"x27" |
| 74 | 32.00 | 15", 18" | 18" |

TOTAL MODELED AREA 1180.04

NOTE: DNM - Did Not Model

TABLE 2 (cont.)

INDIAN LAKE

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 3 | 178.35 | 24", 21", 18", 15", 12" | 24" |
| 4 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 5 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 8 | 51.30 | 12", 36" | 36" |
| 9 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 10 | 58.60 | 48", 36", 30", 24" | 48" |
| 12 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 15 | 62.18 | 24", 21", 18" | 24" |
| 16 | 75.03 | 36", 24", 15", 12" | 36" |
| 17 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 18 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 19 | 29.50 | 10", 12", 15", 18" | 12" |
| 20 | 42.90 | 24", 30" | 30" |
| 21 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 22 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 23 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 24 | 109.70 | (1000)— 15" | 15" |
| | | (1002)— 24", 30", 34", 20" | 24" |
| 124 | 84.90 | 84", 48", 30", 36", 24", 15" | 84" |

TOTAL MODELED AREA 692.46

NOTE: DNM - Did Not Model

<u>TABLE 2</u> (cont.)

KENDRICK

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 2 | 213.81 | 18", 15", 42"x48", 24"x60", 48", 36", 30", 20" | 24"x60" |
| 6 | 110.23 | 48", 33", 36", 30", 24", 18", 15" | 18" |
| 7 | 37.59 | 24", 20", 18" | 24" |
| 11 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 125 | 98.60 | 39", 36", 27", 24", 20", 18", 16", 15", 12" | 39" |
| 130 | 156.53 | 42", 36", 30", 24", 20", 18", 15" | 42" |
| 134 | 61.98 | 36", 33", 20", 18", 15" | 36" |
| 135 | 84.00 | 42"x28", 24", 15", 12" | 42x28" |
| 138 | 38.50 | 30", 18", 15", 12", 10" | 30" |

TOTAL MODELED AREA 801.24

NOTE: DNM - Did Not Model

TABLE 2 (cont.)

KETTLE BROOK

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 63 | 13.60 | 12", 15" | 15" |
| 64 | DNM | INSUFFICIENT PIPE DATA | |
| 65 | 404.90 | (1000) — 20", 24", 27" 30", 36", 48" | 48" |
| | | (1002) — 15", 18", 16"x24" | 16"x24" |
| 76 | 46.00 | 15" | 15" |
| 77 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 78 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 79 | 15.60 | 12", 15" | 15" |
| 80 | 447.00 | 39", 30", 42", 36", 24" | 39" |
| 81 | 65.10 | 18", 24", 27", 36", 48" | 36" |
| 82A | 24.40 | 12" | 12" |
| 82 | 15.20 | 12", 15", 18" | 18" |
| 83 | 25.90 | 24" | 24" |

TOTAL MODELED AREA 1057.7

NOTE: DNM - Did Not Model

LAKE QUINSIGAMOND

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 1 | 149.25 | 24", 18", 12" | 24" |
| 100 | 40.30 | 18", 24", 30" | 30" |
| 101 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 102 | 24.70 | 12" | 12" |
| 103 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 104 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 105 | 23.90 | 12" | 12" |
| 106 | 54.10 | (1000) — 21", 18" | 21" |
| | | (1002) — 21", 18" | 21" |
| 107 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 108 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 109 | 97.10 | 24", 30", 36" | 36" |
| 110 | 607.00 | 15", 18", 24", 30",34", 36", 42", 50", 60", 68", 72", 84"x54" | 60" |
| 111 | 243.90 | 18", 24", 30" | 24" |
| 112 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 113 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 114 | 225.20 | 60", 48", 42", 36", 33", 24", 27", 20", 15" | 36" |
| 115 | 125.80 | 15", 18", 20", 24", 36" | 36" |
| 116 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 117 | 79.90 | (1000)— 30", 24", 21" | 30" |
| | | (1002)— 48", 24", 20", 12", 15", 18" | 48" |
| | | (1004)— 30", 24", 18" | 30" |

NOTE: DNM - Did Not Model

LAKE QUINSIGAMOND (cont.)

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 118 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 119 | 291.80 | (1000) — 15", 18", 20", 27", 48" 24", 30", 36", 40" | 36" |
| | | (1002) — 36", 30", 24", 20", 15" | 20" |
| 120 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 121 | 54.20 | 18", 21", 24", 30" | 30" |
| 126 | 155.10 | (1000) — 36" | 36" |
| | | (1002) — 27", 24", 20", 18", 30" 39", 36", 33" | 27" |
| 127 | 50.44 | 24", 18", 15", 12" | 24" |
| 128 | 40.00 | 42" | 42" |
| 129 | 106.86 | 36", 30", 24", 18", 15" | 30" |
| 131 | 110.11 | 36", 30", 20", 18", 15", 12", 10" | 36" |
| 132 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 133 | 47.07 | 15", 12" | 15" |
| 136 | 108.03 | 36", 24", 18", 15", 12" | 36" |
| 137 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 204 | DNM | SMALL PIPES OR DRAINAGE AREA | |

TOTAL MODELED AREA 2634.76

MIDDLE RIVER

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 75 | 39.40 | 24", 16 x 24" | 24" |
| 84 | 59.90 | 54", 36", 33", 24", 18" | 54" |
| 85 | 44.70 | 24", 15" | 24" |
| 86 | 66.20 | 24", 20", 18", 15" | 24" |
| 87 | 70.50 | 36", 33", 31x35",24x30",16x24" | 36" |
| 88 | 16.40 | 18", 15" | 18" |
| 89 | 56.90 | 12" | 12" |

TOTAL MODELED AREA 354

NOTE: DNM - Did Not Model

MILL BROOK

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 57 | 159.50 | 12", 15", 18", 20", 24",28" 30", 22" X 33", 20"x30" | 30" |
| 122 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 123 | 28.04 | 24" | 24" |
| 139 | 19.20 | 12" | 12" |
| 140 | 48.60 | 15", 18", 24" | 24" |
| 141 | 147.90 | 42", 48" | 48" |
| 142 | 100.80 | 15", 20", 24", 30", 34", 36" | 36" |
| 143 | 166.30 | 66", 36", 30", 24" | 66" |
| 144 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 145 | 88.00 | 20", 24", 30", 32" | 32" |
| 146 | DNM | COMBINED | |
| 147 | 27.20 | 24", 18"x27" | 18"x27" |
| 148 | DNM | COMBINED | |
| 149 | 20.00 | 12", 24", 30" | 30" |
| 150 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 151 | DNM | COMBINED | |
| 152 | 74.30 | 18", 30", 36", 42", 24"x36" | 42" |
| 152A | 34.00 | 15", 20", 24" | 24" |
| 153 /156 | DNM | COMBINED | |
| 154 | DNM | COMBINED | |
| 155 | DNM | COMBINED | |
| 157 | DNM | COMBINED | |
| 158 | DNM | COMBINED | |
| 159 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 160 | DNM | COMBINED | |
| 161 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 162 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 163 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 164 | DNM | COMBINED | |
| 165 | DNM | COMBINED | |
| 166 | DNM | COMBINED | |
| 167 | DNM | COMBINED | |
| 168 | DNM | COMBINED | |
| 169 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 170 | DNM | SMALL PIPES OR DRAINAGE AREA | |

NOTE: DNM - Did Not Model

MILL BROOK (cont.)

| OUTFALL | AREA (ACRES) | PIPE SIZES MODELED | OUTFALL PIPE SIZE |
|---|---|---|---|
| 171 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 172 | DNM | COMBINED | |
| 173 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 174 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 175 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 176 | DNM | COMBINED | |
| 177 | DNM | COMBINED | |
| 178 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 179 | DNM | COMBINED | |
| 180 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 181 | DNM | SMALL PIPES OR DRAIANGE AREA | |
| 182 | 26.74 | 24", 16"x24", 18"x27", 20"x30" | 20"x30" |
| 183 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 184 | 35.00 | 18"x27", 20"x30", 24"x36" | 24"x36" |
| 185 | 9.40 | 12", 16"x24", 18"x27", 26"x39" | 26"x39" |
| 186 | 44.61 | 12", 15", 18", 33", 16"x24", 18"x26", 18"x27" | 33" |
| 187 | 23.10 | 20"x30", 24"x36", 36" | 24"x36" |
| 188 | DNM | COMBINED | |
| 189 | DNM | COMBINED | |
| 190 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 191 | 21.60 | 12", 15", 18" | 18" |
| 192 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 193 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 194 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 195 | DNM | SMALL PIPES OR DRAINAGE AREA | |
| 196 | 209.20 | 42", 20x30", 18x27", 30", 34", 36", 24", 20" | 42" |
| 197 | DNM | COMBINED | |
| 198 | DNM | COMBINED | |

TOTAL MODELED AREA 1117.19

NOTE: DNM - Did Not Model

## II. STORM WATER MANAGEMENT MODEL (SWMM)

### A. SWMM DESCRIPTION

The Environmental Protection Agency's Stormwater Management Model (SWMM) is a mathematical model which can simulate synthetic or historic storm events on the basis of rainfall hyetographs and system characterization to predict outflows in the form of hydrographs. All aspects of the urban hydrologic cycles are simulated, including surface runoff and transport through a drainage network. SWMM was initially developed in 1970, and has since been updated and modified by the University of Florida, Metcalf & Eddy, Inc., and Camp, Dresser & McKee, Incorporated. This portion of the report is not a substitute for describing in detail the various aspects of the SWMM. The user should refer to the Storm Water Management Model, Version 4: User's Manual for further information.

The process of modeling the Worcester storm drainage system consisted of developing two major components of the SWMM application. These are the:

1) Runoff Block, and
2) Transport Block.

The purpose of the Runoff Block is to develop surface runoff hydrographs at desired inlets to the storm drainage pipe network. The input to this block consists of a rainfall hyetograph and hydrologic characterization of the drainage area including area of each catchment, percent imperviousness, and slope. The hydrographs are required as input to the Transport Block which subsequently models the stormwater pipe network.

The purpose of the Transport Block is to route the surface runoff hydrographs developed in the Runoff Block through the pipe network to the outfall. This block produces outfall hydrographs and identifies surcharged elements of the pipe network. However, it does not accurately model surcharged conditions in pipes, nor does it account for backwater effects or pressure flows which may develop in the pipe network. A more accurate method for modeling the pipe network may be obtained by utilizing the Extended Transport (EXTRAN) Block of SWMM. EXTRAN has the ability to simulate pressure flows and surcharge, however it is not capable of modeling water quality. The Transport Block was chosen by the City of Worcester to be used in this simulation due to its capability for simulating pollutant load routing through the storm drain pipe network.

The Graph Block plots hydrographs which were developed in either the Runoff Block or the Transport Block. The Runoff and Transport Blocks are briefly described in the following sections, however, the SWMM User's Manual should be referred to for an in-depth description and further information concerning the various parameters. The input/output of these two blocks is summarized in Appendix 1. Figure 2 illustrates the sequence of input, block applications, and output for this model.

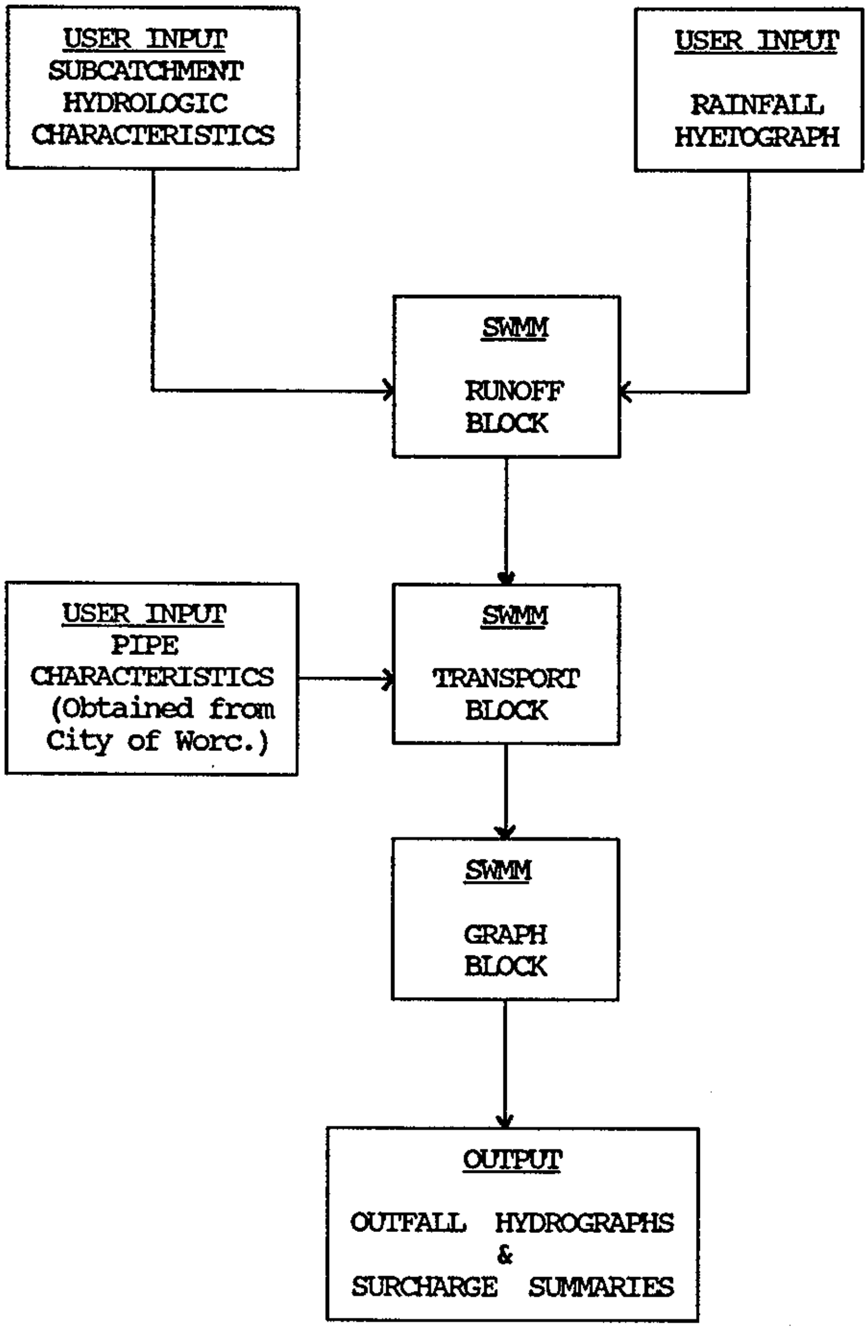

USER INPUT
SUBCATCHMENT
HYDROLOGIC
CHARACTERISTICS
USER INPUT
RAINFALL
HYETOGRAPH
SWMM
RUNOFF
BLOCK
USER INPUT
PIPE
CHARACTERISTICS
(Obtained from
City of Worc.)
SWMM
TRANSPORT
BLOCK
SWMM
GRAPH
BLOCK
OUTPUT
OUTFALL HYDROGRAPHS
&
SURCHARGE SUMMARIES

FIGURE 2

1. Runoff Block

Description/Capabilities

The Runoff Block forms the source of runoff hydrographs for most other SWMM applications. The input data for this block is extremely important since it is used within the Transport Block to generate the outfall hydrograph. The Runoff Block accepts a rainfall hyetograph; predicts runoff from the subcatchments on the basis of their individual characteristics, and determines the inflow hydrographs at the inlets (subcatchments) to the drainage pipe network.

Each individual outfall drainage area is divided into subcatchments. The Runoff Block generates and routes the surface water runoff from these subcatchments into the drainage pipes. Subcatchments are represented as idealized runoff areas with uniform slope. Parameters describing the physical characteristics of the subcatchment such as roughness values, depression storage, and infiltration values, are constant throughout this particular study.

Water flowing into an inlet point is the sum of all the direct drainage from subcatchments into that inlet. A continuity check is made for the disposition of the rainfall water in the form of surface runoff, infiltration, and evaporation losses. The error in continuity is computed and then printed as a percentage of precipitation.

Surface runoff in this model is accomplished using an overland flow subroutine which routes flow into an inlet (manhole). This is done using the subcatchment elements which describe the physical characteristics of each individual subcatchment. These elements are width of subcatchment (feet), area (acres), percent imperviousness, ground slope, and Manning's roughness coefficients for both pervious and impervious areas. Values of percent imperviousness were estimated using topographic maps (1"=100') developed by Moore Survey and Mapping Corporation. Depression storage (i.e., surface ponding) is set at zero for this model to provide a more conservative estimate of runoff volume. By not modeling depression storage, a larger volume of runoff is obtained. Flow routing through the subcatchments is accomplished by approximating them as non-linear reservoirs. A detailed description of the surface runoff flow generation is contained in Appendix V of the SWMM User's Manual. The surface flow from subcatchments is always routed to inlets (manholes) of the stormwater conveyance system. The Transport Block subsequently models the routed inflow through the stormwater conveyance system.

Infiltration losses are calculated using Horton's Equation. Horton's Equation is an empirical infiltration model, however, SWMM uses an integrated form of the equation to avoid an unwarranted reduction in the infiltration capacity during periods of light rainfall. Horton's Equation determines the infiltration capacity of the soil based on the initial (dry) infiltration capacity, the final (equilibrium) infiltration capacity, and a constant representing the rate of decrease in infiltration capacity. These three parameters were determined from the American Society of Civil Engineers (ASCE) Manual of Engineering Practice, No. 28.

For sandy soil, the ASCE Manual recommends an initial infiltration capacity of about 0.5 inch per hour, the equilibrium infiltration capacity of 0.1 inch per hour, and the rate of decrease assumed to be 0.001 inch per hour.

Since single event simulations are insensitive to evaporation rates, the default evaporation rate value provided by SWMM is used throughout the modeling process.

Limitations

Limitations of the Runoff Block did not seriously impact the modeling required for this study. Table 4-3 (Page 88) of the SWMM manual compares flow routing characteristics of the Runoff Block, Transport Block, and the Extended Transport (EXTRAN) Block. For example, no pressure flow, flow reversal, or backwater effects are accounted for in the The Runoff Block. The Runoff Block is not used for routing flow through channels or pipes in this particular model. Instead, all flow routing through Worcester's storm drainage network is accomplished using the Transport Block, which is briefly described in the next section.

## 2. Transport Block

### Description/Capabilities

Routing stormwater flows through the pipe network is accomplished using the Transport Block. This block has been used only for routing of stormwater quantities, and did not involve routing of quality parameters or estimating dry weather flow or infiltration.

Each component of the pipe network is classified as a certain type of "element". All elements in combination form a conceptual representation of the system. Elements used in the modeling of the Worcester system included manholes and conduits. Flow routing proceeds downstream through all elements during each increment in time until the storm inlet hydrographs developed in the Runoff Block have been passed through the entire system. The flow routing process acts as a "cascade" of elements, each discharging into the next with no other interactions. When the capacity of a conduit is exceeded, a "surcharge" is indicated in the output for that element. The final product is a hydrograph at the outfall and a summary of the surcharged conduits.

The physical representation of the pipe network is characterized by a system of conduit lengths, joined at manholes. Inflows, calculated from the Runoff Block, are allowed to enter the system only at manholes. Thus, manholes must be located at points corresponding to inlet points for hydrographs generated by an external block, such as the Runoff Block. These hydrographs are then routed through the pipe network to produce the final hydrograph at the outfall.

### Limitations

The solution procedure for flow routing follows a kinematic wave approach which allows disturbances to propagate only in the downstream direction. Consequently, backwater effects are not modeled beyond that of a single conduit, and downstream conditions are assumed not to affect upstream conditions. Table 4-3 (Page 88) of the SWMM manual compares flow routing characteristics of the Runoff, Transport, and Extended Transport (EXTRAN) Blocks. The Transport Block has the same limitations exhibited by the Runoff Block. Flow reversal, pressure flow, and backwater effects are not modeled.

When calculating flows in each element, the upstream flows are summed and added to any surface runoff which is allowed to enter the system only at a non-conduit element (manhole). A check for surcharging of the conduit element is then made. If the inflow exceeds the conduit capacity, the excess flow is stored at the nearest upstream manhole. SWMM is unable to tell depth of possible flooding, only that there is a surcharge at a particular manhole. The conduit is assumed to operate at full-flow capacity until the excess flow can be transmitted. According to the SWMM manual "...Pressure-flow conditions are not explicitly modeled and no attempt is made to determine if ground flooding exists." The pipe capacity is limited to the maximum flow produced by gravity with no increase due to pressure.

The SWMM manual further states that "...The Transport Block has proven its ability to model accurately flows in most sewer systems, within the limitations" of the backwater and surcharging effects, "and as such it should be adequate for many applications." However, the Transport Block will not accurately simulate systems with extensive interconnections, loops, flow reversals, significant backwater effects, or systems where surcharging is treated as pressure-flow. The Extended Transport Block is better suited for these conditions.

Infiltration into the system was not modeled. According to the SWMM manual, "...Concurrent historical rainfall, water table, and sewer flow data of several weeks' duration are needed to completely describe infiltration." This effort was not within the scope of this study.

## III. WORCESTER ANALYSIS

### A. METHODOLOGY

The modeling process for the City of Worcester was conducted in two phases. The first phase was a Pilot Study to determine the appropriate methodology and its suitability in applying it to the entire drainage system. The second phase included applying this methodology to the remaining drainage and outfall areas not included in the Pilot Study.

The city was first divided into ten drainage areas. The Beaver Brook Drainage Area was chosen as the area to be used for a Pilot Study because it contains representative land use types and was complex enough to develop a methodology which could then be applied to the remaining drainage areas of the city. The outfalls and their respective pipe network boundaries were then identified using the Fay, Spofford, and Thorndike, Inc. storm drain sewer maps.

Based on the Pilot Study conducted for the Beaver Brook drainage area, a methodology for modeling was developed and applied to the remaining nine drainage areas.

#### Outfalls

Each outfall was modeled separately and has its' own input file. Where an outfall is tributary to another outfall, the output hydrograph for the tributary area was input to the downstream outfall. Outfalls consisting of simple lines, small tributary areas, or combined sewers were not modeled.

#### Selection of Rainfall Event

A precipitation event was selected (10 Year, 25 Year, etc.) as input as a rainfall hyetograph. The precipitation event modeled for the Pilot Study was the recent 13 March 87 storm which is comparable to a 10 year - 24 hour rainfall event. However, a 25-year 24-hour rainfall event was used for all of the outfall areas to reflect the city's design storm event for their drainage system. The total precipitation for this design storm event equals 5.33 inches and was taken from the U.S. Weather Bureau's Technical Publication (T.P.) No. 40.

Various rainfall distributions of the total amount of precipitation (5.33 inches) were examined in T.P. 40. Using the appropriate rainfall distribution from T.P. 40 for a 25-year event resulted in a peak one hour rainfall of 2.1 inches. This quantity of rainfall over this small, one hour duration would have surcharged most of the storm drain system, resulting in surcharged storage in each of the outfall pipe networks. Since one of the limitations of the Transport Block is that it does not compute pressure flows from surcharging, the chosen T.P. 40 distribution would have resulted in less meaningful information regarding output hydrographs. Therefore, the adopted distribution is based on the 31 March 1987 storm event as recorded at Worcester Airport. The T.P. 40 25-year 24-hour rainfall total of 5.33 inches was applied to this adopted distribution to develop the 25-year design storm event required for this study. Although this 25-year design storm event has three independent peaks, review of rainfall records at Worcester Airport revealed that this type of almost constant rainfall distribution with peak rainfall totals between 0.3 and 0.7 inches per hour is common for 24-hour rainfall events. The total precipitation from the 31 March 1987 event (4.55 inches) also approximates the 25-year total of 5.33 inches estimated by T.P. 40. Figure 3 is the rainfall hyetograph for the 25 Year event.

SWMM Input Files

Development of the SWMM input file for each outfall consisted of four parts:

1. Runoff Block

2. Transport Block

3. Graph Block

4. Combine Block

Runoff Block

The Runoff Block was used to route the flow from the tributary area to the storm drain system. In the runoff block, the tributary area (catchment) to an outfall was subdivided into subcatchment areas. The subcatchment output hydrographs generated for a selected storm event were then routed to the main lines of the storm drain system. Subcatchment boundaries and parameters for the runoff block (% imperviousness, subcatchment areas, subcatchment width and slope) were estimated using topographic maps provided by the city. The maps are 1"=100' scale and were developed by Moore Survey and Mapping Corporation.

Transport Block

The main pipelines to an outfall were modeled using the Transport Block. In general the main pipelines are greater than or equal to 36 inches in diameter, however, where there are no lines of this diameter in an outfall tributary area, smaller lines were modeled. The transport block assumes that runoff flows directly into a manhole and that there is free outfall at the discharge point.

Pipe data (invert elevations, diameters) were collected from the city using sewer maps developed by Fay, Spofford, and Thorndike, Inc.. These maps show the city's storm sewer system and were utilized for identifying outfalls and developing data for both the Runoff and Transport Blocks. Pipes of similar diameter and slope were modeled as a single line. Slopes were calculated based on the invert elevations provided by the city. As agreed to with the City of Worcester, a Manning's Roughness Coefficient "n" value of 0.014 was assumed for all pipes.

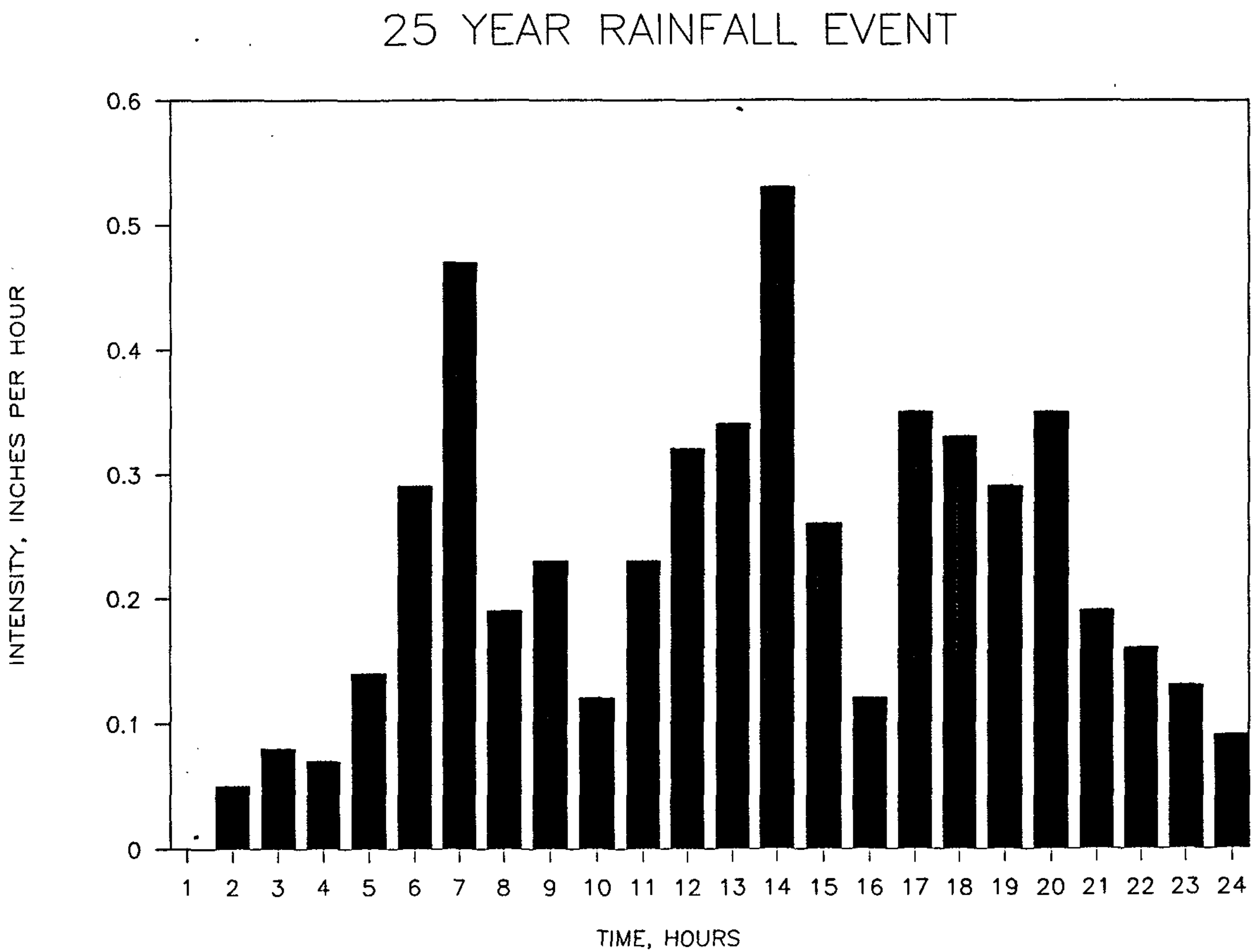

25 YEAR RAINFALL EVENT
INTENSITY, INCHES PER HOUR
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
TIME, HOURS

**FIGURE 3**

Due to SWMM program constraints and limits on the quantity of data to be processed, it was not possible to model every conduit within a drainage basin. SWMM is not designed for individual pipe analysis. Instead it is intended to provide an overall model of outfall discharges in a storm sewer system. Consequently, individual conduits have been aggregated into larger ones. Average slopes for same size pipes have been used to reduce the amount of data required for input to the model. If there was a relatively large change in slope from steep to shallow of an aggregated pipe section, a division was made at that point to more accurately model existing conditions. This was done to avoid simulated surcharge conditions that would not occur in reality. In general, to simplify the overall procedure, pipes less than thirty inches in diameter were not modeled. However, numerous exceptions were made in areas that did not contain larger pipes or in areas where it was judged necessary to provide adequate modeling of the pipe network. Refer to Table 2 for a complete list of the pipe sizes which were modeled in each specific outfall area.

Graph Block

The Graph Block is the third block to be run in the model. Line printer plots of desired output hydrographs may be obtained from the Graph Block. However, desired output hydrographs to be plotted by the Graph Block must first be designated in the Transport Block. See Appendix 1 - Transport Block.

Combine Block

The Combine Block was also used in a few instances. This block allows the manipulation of interface files to aggregate results from a previous run into subsequent blocks. The Combine Block was used in the following instances:

Kettle Brook

AREA 63 drains into Manhole Number 120 of AREA 65.
AREA 79 drains into Manhole Number 46 of AREA 80.

Beaver Brook

AREAS 13, 14, 25, 199, 200, and 201 all drain into Manhole Number 66 of AREA 26.

Using the Beaver Brook Drainage Area as an example, the sequence required to run the Combine Block is as follows:

1. Use SWMM to run all of the data files for the areas which are to be combined. (i.e., AREA13.DAT)
2. An interface file is created for each data file which is run (i.e., AREA13T.INT). This interface file is required by the Combined Block.
3. The files named COMBINE_.DAT are then run by SWMM. These files take each hydrograph developed by SWMM for the outfall areas to be combined and forms a single cumulative hydrograph to be input to the "downstream" outfall area.

4. In this example, the file named BEAVERBK.DAT is then used to route the combined hydrograph plus AREA 26's own surface runoff flow through its pipe network to the outfall location.

SWMM Output

The SWMM output consists of hydrographs at each outfall plus identification of surcharges in the modeled pipe system which are tributary to the outfall. Hydrographs at intermediate manholes may also be printed out, however, only the outfall hydrographs are presently designated for printing.

Numbering System

The numbering system used for the modeling was designed for ease of understanding. Each of the outfall areas was first given a unique number. The pipe and manhole elements of the modeled outfall areas were then numbered in ascending order from the actual outfall location, working backwards into the drainage area specifically defined for that outfall. The outfall location was numbered "1000". However, during the pipe data collection phase, it was discovered that certain areas actually contained two or more distinct discharge pipes. In Table 2, outfall numbers followed by -1000, -1002, and -1004 are those which contain two or more discharge pipes. The outfall areas shown on Plates 2-12 are a gross representation of the drainage area for that particular outfall.

The first pipe upstream from the outfall is then numbered "1", with the first manhole being numbered "2". Therefore, all subsequent manholes are even numbers, and pipes/conduits are odd numbers for that particular outfall. Subcatchments are numbered according to the manhole number which receives the runoff from that particular subcatchment. Separate Input/Data files have been developed for each modeled outfall area so that the same numbering system could be used throughout the modeling process.

B. ASSUMPTIONS

Some of the assumptions used in this SWMM study were:

- o All pipe network characterizations (size, slope, length) were provided by the City of Worcester from their storm drain maps.
- o No combined sewers (i.e., conveying both sanitary and storm water flows) were modeled.
- o Single pipes draining small tributary areas were usually not modeled.
- o Slopes for portions of the pipe network were estimated when sufficient data was not available.
- o All drainage areas are assumed to be contained wholly within the city limits.

- o Where there were two pipe sizes specified between manholes, the smaller of the two pipe sizes was modeled. The decision to model only one of the two pipe sizes was due to insufficient data on the length for each particular pipe.

- o At the city's request, Manning's Roughness coefficient (n) was assumed constant for all pipes and subcatchments. (n = 0.014)

- o Due to the large volume of data required to model the city's storm drain system, only pipes 30" in diameter or greater were modeled. However, within a specific outfall area there may be pipes smaller than 30" which were modeled in order to provide a more detailed analysis of the conveyance system within that particular outfall area.

- o Depression storage within a subcatchment was not modeled. This results in a larger volume of runoff being generated from the subcatchment, and therefore a more conservative estimate.

C. ANALYSIS OF OUTFALL AREAS

Each outfall's output was analyzed to check the relative accuracy of the output and for any errors which may be corrected. The outfall hydrographs for all of the areas are shown on separate plates.

The input and output files for each outfall area are shown in Appendix 3. Table 3 is a summary of the peak flows (cfs) which occurred at each outfall location.

TABLE 3

BEAVER BROOK

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 13 | 16.20 |
| 14 | 25.00 |
| 25 | 19.70 |
| 26 | 372.00 |
| 40 | 29.50 |
| 45 | 128.00 |
| 46 | 3.94 |
| 54 | 16.80 |
| 55 | DNM |
| 56 | 59.7 |
| 58 | 20.60 |
| 59 | DNM |
| 60 | DNM |
| 61 | DNM |
| 71 | DNM |
| 72 | 46.00 |
| 73 | DNM |
| 199 | 2.65 |
| 200 | 24.10 |
| 201 | 19.20 |
| 202 | DNM |
| 203 | DNM |

BLACKSTONE

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 90 | 44.50 |
| 91 | 31.50 |
| 92 | 34.20 |
| 93 | 40.60 |
| 94 | 50.90 |
| 95 | DNM |

BROAD MEADOW BROOK

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 96 | 113.00 |
| 97 | 16.50 |
| 98 | DNM |
| 99 | 8.84 |

COES RESERVOIR

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 27 | 77.30 |
| 28 | 16.40 |
| 29 | 15.70 |
| 30 | 38.20 |
| 31 | DNM |
| 32 | 81.30 |
| 33 | DNM |
| 34 | DNM |
| 35 | DNM |
| 36 | DNM |
| 37 | DNM |
| 38 | 44.70 |
| 39 | 95.70 |
| 41 | DNM |
| 42 | DNM |
| 43 | 17.00 |
| 44 | DNM |
| 47 | 9.58 |
| 48 | 7.40 |
| 49 | 8.80 |
| 50 | DNM |
| 51 | DNM |
| 52 | 12.40 |
| 53 | (1000) 9.18 |
| | (1002) 27.5 |
| 62 | 14.67 |
| 66 | DNM |
| 67 | DNM |
| 68 | DNM |
| 69 | DNM |
| 70 | 25.20 |
| 74 | 11 70 |

INDIAN LAKE

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 3 | 29.20 |
| 4 | DNM |
| 5 | DNM |
| 8 | 20.40 |
| 9 | DNM |
| 10 | 28.10 |
| 12 | DNM |
| 15 | 27.10 |
| 16 | 28.20 |
| 17 | DNM |
| 18 | DNM |
| 19 | 4.97 |
| 20 | 19.00 |
| 21 | DNM |
| 22 | DNM |
| 23 | DNM |
| 24 | (1000) 16.00 |
| | (1002) 17.20 |
| 124 | 42.00 |

KENDRICK

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 2 | 86.50 |
| 6 | 40.40 |
| 7 | 16.80 |
| 11 | DNM |
| 125 | 32.50 |
| 130 | 52.70 |
| 134 | 28.30 |
| 135 | 26.30 |
| 138 | 10.70 |

NOTE: DNM - Did Not Model

MILL BROOK

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 57 | 34.90 |
| 122 | DNM |
| 123 | 12.50 |
| 139 | 9.20 |
| 140 | 16.20 |
| 141 | 77.80 |
| 142 | 47.70 |
| 143 | 81.80 |
| 144 | DNM |
| 145 | 35.70 |
| 146 | DNM |
| 147 | 12.00 |
| 148 | DNM |
| 149 | 8.80 |
| 150 | DNM |
| 151 | DNM |
| 152 | 32.90 |
| 152A | 7.13 |
| 153 | DNM |
| \156 | |
| 154 | DNM |
| 155 | DNM |
| 157 | DNM |
| 158 | DNM |
| 159 | DNM |
| 160 | DNM |
| 161 | DNM |
| 162 | DNM |
| 163 | DNM |
| 164 | DNM |
| 165 | DNM |
| 166 | DNM |
| 167 | DNM |
| 168 | DNM |
| 169 | DNM |
| 170 | DNM |

MILL BROOK (cont.)

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 171 | DNM |
| 172 | DNM |
| 173 | DNM |
| 174 | DNM |
| 175 | DNM |
| 176 | DNM |
| 177 | DNM |
| 178 | DNM |
| 179 | DNM |
| 180 | DNM |
| 181 | DNM |
| 182 | 12.70 |
| 183 | DNM |
| 184 | 16.50 |
| 185 | 4.35 |
| 186 | 8.36 |
| 187 | 10.40 |
| 188 | DNM |
| 189 | DNM |
| 190 | DNM |
| 191 | 10.40 |
| 192 | DNM |
| 193 | DNM |
| 194 | DNM |
| 195 | DNM |
| 196 | 87.70 |
| 197 | DNM |
| 198 | DNM |

KETTLE BROOK

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 63 | 5.25 |
| 64 | DNM |
| 65 | (1000) 88.70 |
| | (1002) 44.30 |
| 76 | 20.60 |
| 77 | DNM |
| 78 | DNM |
| 79 | 7.27 |
| 80 | 78.90 |
| 81 | 30.60 |
| 82A | 11.00 |
| 82 | 6.89 |
| 83 | 11.70 |

LAKE QUINSIGAMOND

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 1 | 10.50 |
| 100 | 18.40 |
| 101 | DNM |
| 102 | 11.20 |
| 103 | DNM |
| 104 | DNM |
| 105 | 10.90 |
| 106 | (1000) 18.70 |
| | (1002) 5.97 |
| 107 | DNM |
| 108 | DNM |
| 109 | 41.70 |
| 110 | 270.00 |
| 111 | 30.60 |
| 112 | DNM |
| 113 | DNM |
| 114 | 103.00 |
| 115 | 42.00 |
| 116 | DNM |
| 117 | (1000) 10.10 |
| | (1002) 10.30 |
| | (1004) 12.10 |
| 118 | DNM |
| 119 | (1000) 83.30 |
| | (1002) 26.80 |
| 120 | DNM |
| 121 | 23.6 |
| 126 | (1000) 3.63 |
| | (1002) 61.30 |
| 127 | 16.10 |
| 128 | 17.80 |
| 129 | 36.40 |
| 131 | 51.20 |
| 132 | DNM |
| 133 | 13.60 |
| 136 | 36.70 |
| 137 | DNM |
| 204 | DNM |

MIDDLE RIVER

| OUTFALL | PEAK FLOW (CFS) |
|---|---|
| 75 | 14.00 |
| 84 | 6.10 |
| 85 | 15.30 |
| 86 | 30.40 |
| 87 | 8.78 |
| 88 | 7.57 |
| 89 | 19.20 |

NOTE: DNM - Did Not Model

## D. IDENTIFICATION OF PROBLEM AREAS

The following pages contain Table 4 which provides a summary of surcharged pipes for each outfall area. The surcharges are based on the 25 Year Storm Event used in the modeling process. Since the solution procedure used in the Transport Block does not model backwater effects, downstream conditions are assumed not to affect upstream computations. According to the SWMM manual, "...Surcharging is modeled simply by storing excess flows (over and above the full flow conduit capacity) at the upstream manhole until capacity exists to accept the stored volume. Pressure-flow conditions are not explicitly modeled and no attempt is made to determine if ground surface flooding exists."

It should be noted that many storm sewers are designed with pressure flow, therefore, a surcharged pipe may not necessarily be a problem pipe. A survey of flooding problems would have to be reviewed to accurately determine where problem areas exist due to undersized pipes.

TABLE 4

| DRAINAGE AREA | OUTFALL # | SURCHARGED PIPE #'s | STREET NAME(S) |
|---|---|---|---|
| BEAVER BROOK | | | |
| | 13 | 3 | DICK DR. |
| | 25 | 29 | SALISBURY ST. |
| | 40 | 1 | INTO RIVER BROOK |
| | 45 | NONE | |
| | 46 | 1 | CHANDLER ST. |
| | | 3 | " |
| | | 15 | " |
| | | 21 | " |
| | | 23 | " |
| | 54 | NONE | |
| | 58 | 1 | INTO BEAVER BROOK |
| | | 15 | PARKER ST. |
| | 72 | NONE | |
| | 199 | 1 | SALISBURY ST. |
| | 200 | NONE | |
| | 201 | NONE | |
| BLACKSTONE | | | |
| | 90 | 1 | ENTERS BLACKSTONE @ R+R TRACKS |
| | 91 | NONE | |
| | 92 | 1 | GREENWOOD ST. |
| | 93 | 1 | GREENWOOD ST. |
| | 94 | 9 | BALLARD ST. |
| BROAD MEADOW | | | |
| | 96 | 15 | EDISON ST. |
| | | 61 | DUNKIRK AVE. |
| | 97 | NONE | |
| | 99 | NONE | |
| COES | | | |
| | 27 | NONE | |
| | 28 | 1 | MOWER ST. |
| | 29 | NONE | |
| | 30 | NONE | |
| | 32 | NONE | |
| | 38 | 25 | PLEASANT ST. |
| | 39 | NONE | |
| | 43 | 3 | EASEMENT |
| | 47 | NONE | |
| | 48 | NONE | |
| | 49 | 1 | END OF SWEETBRIER LANE |
| | 52 | NONE | |
| | 53 | NONE | |
| | 62 | NONE | |
| | 70 | 7 | MAIN ST. |
| | | 19 | " |
| | | 31 | " |

TABLE 4 (cont.)

| | | | |
|---|---|---|---|
| COES | 74 | 1 | BROOK @ WEBSTER ST. |
| | | 17 | MAIN ST. |
| INDIAN LAKE | | | |
| | 3 | 1 | HOLDEN ST. |
| | | 21 | " |
| | 8 | 3 | LESLIE RD. |
| | 10 | NONE | |
| | 15 | NONE | |
| | 16 | NONE | |
| | 19 | 3 | SHERBURNE AVE. |
| | 20 | NONE | |
| | 24 | 31 | FOREST ST. |
| | | 41 | " |
| | 124 | NONE | |
| KENDRICK | | | |
| | 2 | NONE | |
| | 6 | 1 | ARARAT ST. @ THE BROOK |
| | 7 | NONE | |
| | 125 | 37 | SUMMERHILL AVE. |
| | | 57 | KING PHILLIP RD. |
| | | 63 | " |
| | | 97 | CHRISTINE RD. |
| | 130 | 47 | FAIRHAVEN RD. |
| | | 55 | ARLIE ST. |
| | | 57 | " |
| | | 63 | " |
| | | 81 | HILLCROFT AVE. |
| | 134 | NONE | |
| | 135 | 37 | MARLAND RD. |
| | 138 | 19 | TUNIS RD. |
| | | 23 | " |
| KETTLE BROOK | | | |
| | 63 | 1 | VERMONT AVE. |
| | 65 | 153 | SYLVAN ST. |
| | | 149 | SEMINOLE ST. |
| | | 139 | MAIN ST. |
| | | 111 | CULVERT @ MAIN ST. |
| | 76 | NONE | |
| | 79 | NONE | |
| | 80 | 43 | EASEMENT |
| | | 41 | EASEMENT |
| | | 19 | FALCON ST. |
| | | 5 | STAFFORD ST. |
| | 81 | NONE | |
| | 82A | NONE | |
| | 82 | NONE | |
| | 83 | NONE | |
| LAKE QUINSIGAMOND | | | |
| | 1 | 1 | APTHORP ST. |
| | | 3 | " |
| | | 9 | " |

TABLE 4 (cont.)

| | | |
|---|---|---|
| LAKE QUINSIGAMOND | | |
| 100 | NONE | |
| 102 | NONE | |
| 105 | NONE | |
| 106 | NONE | |
| 109 | NONE | |
| 110 | 21 | HAMILTON ST. |
| 111 | 7 | EASEMENT |
| 114 | 67 | EASEMENT |
| 115 | 41 | COBURN AVE. |
| | 45 | WIGWAM AVE. |
| | 51 | ALVARADO AVE. |
| 117 | 17 | COLBY AVE. |
| 119 | 89 | BROOK LINCOLN ST. |
| | 93 | TWIN LINCOLN ST. |
| | 101 | " " |
| 121 | NONE | |
| 126 | 11 | POMPANO RD. |
| | 19 | LONGMEADOW AVE. |
| 127 | 9 | ST. NICHOLAS AVE. |
| 128 | NONE | |
| 129 | 9 | BOYLSTON ST. |
| 131 | NONE | |
| 133 | 1 | GOTHIC AVE. |
| 136 | 25 | QUINAPOXET LANE |
| | 45 | " " |
| MIDDLE RIVER | | |
| 75 | 1 | ENTERS MIDDLE RIVER |
| 84 | 3 | SOUTHBRIDGE ST. |
| 85 | 15 | EASEMENT |
| 86 | NONE | |
| 87 | 5 | EASEMENT |
| | 11 | " |
| 88 | NONE | |
| 89 | 1 | McKEON RD. |
| | 15 | " |
| MILL BROOK | | |
| 57 | 33 | RUTLAND TERRACE |
| | 45 | METCALF ST. |
| | 67 | " |
| | 71 | " |
| | 73 | " |
| 123 | NONE | |
| 139 | NONE | |
| 140 | 9 | W. BOYLSTON TERRACE |
| 141 | NONE | |
| 142 | NONE | |
| 143 | NONE | |
| 145 | NONE | |
| 147 | NONE | |
| 149 | NONE | |
| 152A | 15 | BOYNTON ST. |
| 152 | 49 | DEAN ST. |

TABLE 4 (cont.)

| | | |
|---|---|---|
| MILL BROOK | | |
| 182 | NONE | |
| 184 | NONE | |
| 185 | NONE | |
| 186 | 21 | COMB. WARD ST. |
| | 23 | " |
| 187 | NONE | |
| 191 | NONE | |
| 196 | 47 | TWIN DOANE / PROVIDENCE ST. |

## E. SENSITIVITY ANALYSIS

A sensitivity analysis was performed to determine the output's sensitivity to changes in certain parameters. Outfall hydrographs, and surface runoff from the subcatchments were compared for a range of values of a particular parameter. Outfall Area 13 was chosen for this analysis due to its size and the relative simplicity of its pipe network and subcatchments (only two subcatchments). The outfall hydrographs were developed based on the Pilot Study's 10 Year rainfall event.

Below is a list of parameters for each block which would affect a sensitivity analysis.

Runoff Block:

Line H1: Subcatchment Data

WW3 Percent Imperviousness

Percent Imperviousness is the only parameter in this block which is subject to variability. Manning's Roughness Coefficients for pervious and impervious areas were not chosen because they are assumed to be constant for all subcatchments, and therefore do not affect the sensitivity analysis. The parameters associated with Horton's infiltration equation are typical values used for the New England region and are constant throughout the modeling process. Depression storage is also constant for all outfall areas and will not affect the sensitivity analysis. The SWMM manual also states that "single event simulations are usually insensitive to the evaporation rate." The evaporation rate of 0.1 inches per day is the default value of SWMM, and was used throughout the modeling process. Other parameters in this block describe the conceptualization and physical characterization (slope and width) of the subcatchments within the outfall areas. The level of conceptualization of the outfall areas (i.e., simple vs. detailed) is more important for calibrating and verifying the model's overall performance. This is described further in section "V. Recommendations For Future Work".

Transport Block:

There are no variables from the Transport Block that are suitable for a sensitivity analysis. According to the SWMM User's Manual, flow routing is relatively insensitive to small changes in Manning's roughness coefficient. Other parameters in this block are exclusively for pipe characteristics and are not considered as part of the sensitivity analysis.

Therefore, only one parameter, Percent Imperviousness (WW3), was chosen for the sensitivity analysis.

Summary of Sensitivity Analysis Findings

Varying the value of the percent imperviousness within the Runoff Block was used to determine its sensitivity to specific areas of output. This included:

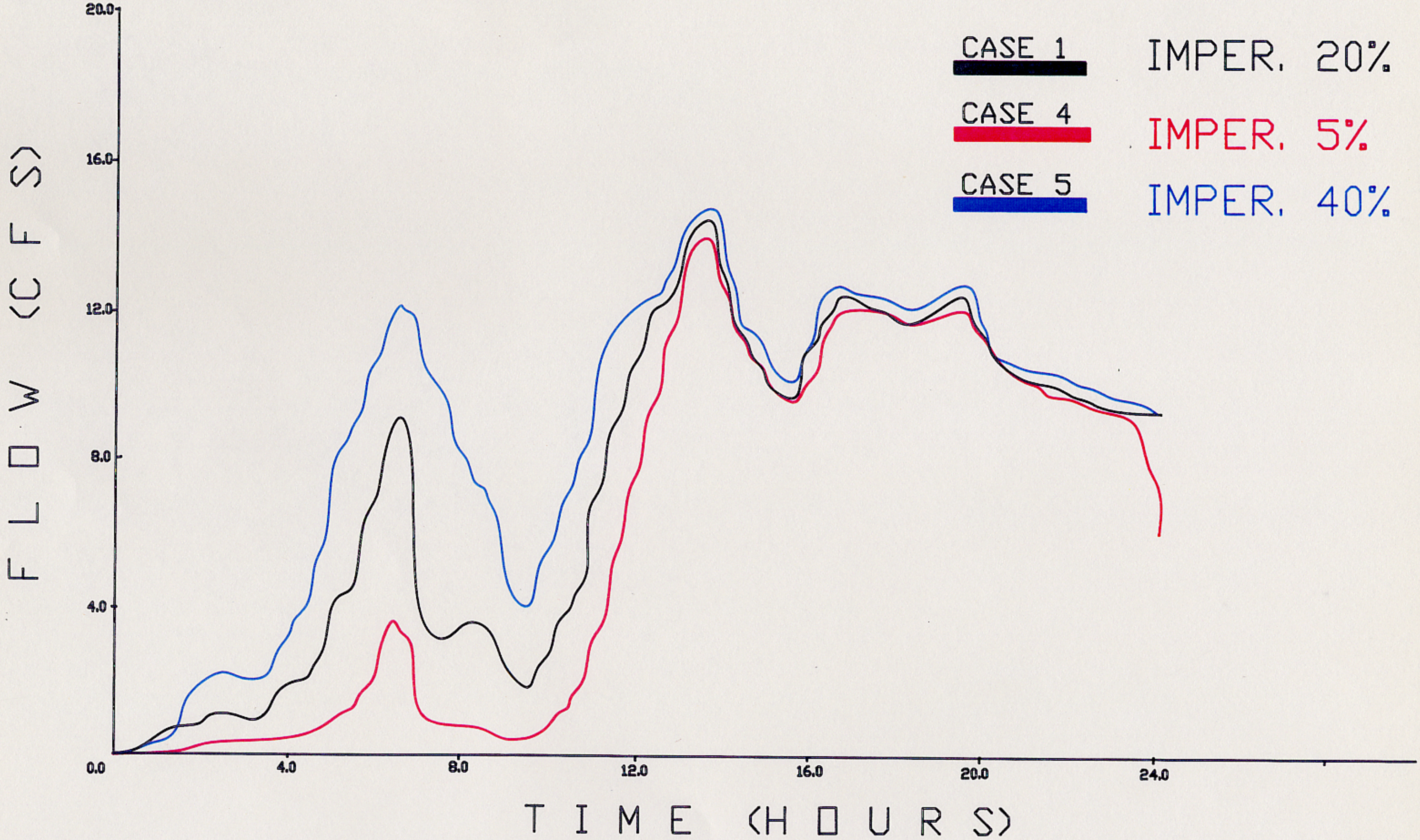
1) Peak Flows at the outfall,
and 2) Surface runoff from the subcatchments.

In order to compare the results of the changing values of the Percent Imperviousness parameter, a "control case" was first established. The "control case" for the sensitivity analysis for WW3 (% Imperviousness) was the Pilot Study input (1987 - 10 Year historic rainfall event) for Area 13. Both subcatchments within this outfall area were given the same percent imperviousness for the "control case". The percent imperviousness of the "control case" was set at 20%. The other cases have both relatively small and large variations in percent imperviousness to show the sensitivity of the output to these variations. Table 5 summarizes the results of the sensitivity analysis. It shows a range of values for each of the above areas of output which correspond to a particular value of percent imperviousness.

TABLE 5

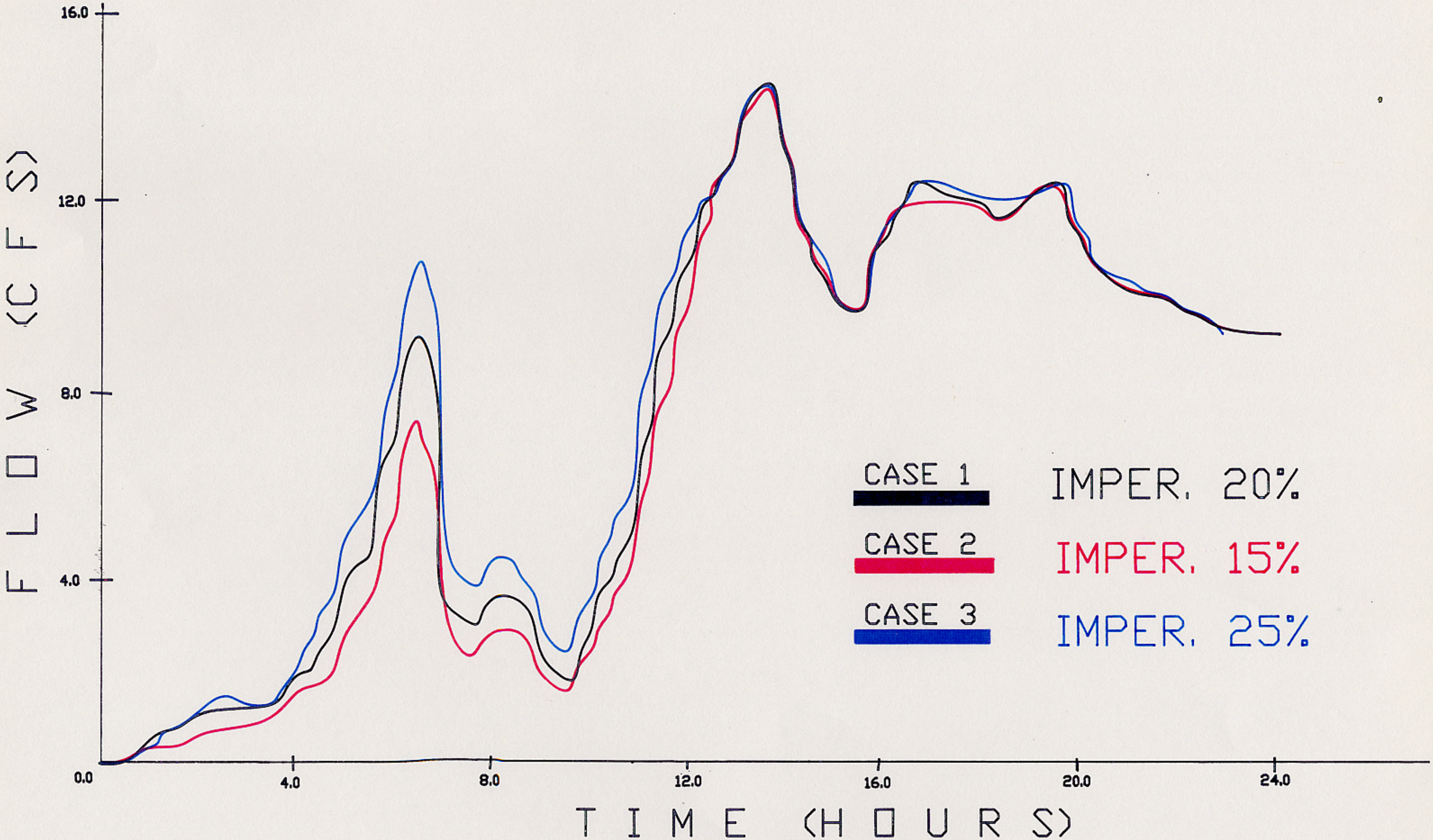
| 1. Outfall Hydrographs | % IMP. | PEAK FLOW (CFS) | % DIFFERENCE FROM CONTROL CASE |
|---|---|---|---|
| Case 1 (Control Case) | 20 | 14.8 | ---- |
| Case 2 | 15 | 14.6 | -1.4% |
| Case 3 | 25 | 14.9 | +0.7% |
| Case 4 | 5 | 14.4 | -2.7% |
| Case 5 | 40 | 15.2 | +2.7% |

| 2. Surface Runoff | % IMP. | SURFACE RUNOFF (CF) | % DIFFERENCE FROM CONTROL CASE |
|---|---|---|---|
| Case 1 (Control Case) | 20 | 683,511.0 | ---- |
| Case 2 | 15 | 632,435.3 | -7.5% |
| Case 3 | 25 | 734,439.2 | +7.5% |
| Case 4 | 5 | 529,938.0 | -22.5% |
| Case 5 | 40 | 886,092.4 | +29.6% |



SENSITIVITY ANALYSIS OF OUTFALL HYDROGRAPHS
BASED ON PERCENT IMPERVIOUSNESS

FIGURE 4




SENSITIVITY ANALYSIS OF OUTFALL HYDROGRAPHS
BASED ON PERCENT IMPERVIOUSNESS

FIGURE 5

1) Figures 4 & 5 are comparisons of outfall hydrographs between the Control Case (Case 1) and Cases 2 through 5. Figure 4 shows that there are significant differences in the hydrograph for large variations in percent imperviousness. The large differences in the hydrograph exhibited between hours 4.0 and 8.0 are due to dry ground conditions resulting in high infiltration over the pervious areas. For example, Case 4 has a low percent imperviousness, or large areas of pervious land. Therefore, much of the initial rainfall will be infiltrated into the soil and will not show up as runoff. However, during the latter half of the storm event, the differences in the hydrographs lessen in magnitude even though the flow rate is high. This is due to the ground being more saturated later in the storm event, thereby producing more runoff. According to Table 5, the peak flows during the storm event exhibit only minor changes of plus or minus 3%.

Figure 5 shows the outfall hydrographs for small variations in percent imperviousness. The changes are similar to those found in Figure 4, only of a lesser magnitude. Table 5 shows that the changes in peak flow (for minor variations in percent imperviousness) are less 1.5%.

As expected, the less impervious a subcatchment is (5% < 20%), the less surface runoff flow there is received by inlets to the drainage system. Increasing the percent imperviousness of a subcatchment from 20% to 40% increases the overland flow entering at the inlets to the pipe drainage network. This is reflected in the outfall hydrograph comparisons of Figures 4 & 5. The sensitivity of the output to this parameter is predictable. A greater value of percent imperviousness, increases overland runoff flow which is carried by the pipe drainage network to the outfall.

2) Surface runoff generated by the Runoff Block can be significantly impacted if the percent imperviousness is not carefully chosen. Minor variations in percent imperviousness (plus or minus 5%) results in changes in volume of surface runoff of plus or minus 7.5%. However, large variations in percent imperviousness such as between 20% and 40% could result in changes of almost 30% in the volume of surface runoff.

Conclusions of Sensitivity Analysis

The sensitivity analysis has concluded that minor variations in determining percent imperviousness (i.e., 20% instead of 25%) do not cause significant changes in the output, specifically the outfall hydrographs or surface runoff volume. However, more significant changes, such as increasing the percent imperviousness from 20% to 40%, or decreasing from 20% to 5% exhibit more pronounced changes in the volume of surface runoff and subsequently the outfall hydrographs. Therefore, it can be concluded that the results obtained from the application of this model are dependent on the accurate selection of percent imperviousness over the entire catchment area for an outfall.

However, according to the SWMM User's Manual, due to the model's flexibility, specific individual modeling decisions (i.e., error in selecting the percent imperviousness of one subcatchment to the pipe network) upstream in the entire catchment (outfall drainage area) will have little effect on the predicted results at the outfall.

## IV. CONCLUSIONS

The SWMM is an extremely helpful tool for stormwater management. However, it is only as accurate as the data which is used as input. Due to limitations in the capabilities of the Transport Block, surcharging effects are not as accurately modeled as can be accomplished using the EXTRAN Block of the SWMM. EXTRAN has the ability to simulate pressure flow and surcharge, however it does not have the capabilities to model water quality. The Transport Block was chosen specifically so that the City of Worcester may use it to model water quality constituents and to simulate pollutant load routing through the pipe network at some future date.

The model in its present form is uncalibrated and unverified. Steps to accomplish the calibration and verification of this model are required in order to successfully utilize it for more accurately predicting the rainfall runoff process along with producing pollutographs and modeling any combined sewers. This is discussed in section "V. Recommendations For Future Work".

## V. RECOMMENDATIONS FOR FUTURE WORK

Future work to be considered by the City of Worcester should include calibrating and verifying the existing model parameters and output. The calibration and verification of the model is recommended, especially prior to any design or future planning based on SWMM results. Calibration is the adjustment of parameters using a specific set of data, and verification is the testing of these parameters using an independent data set. Many computational procedures within the SWMM are based on limited data and are highly empirical. According to the SWMM manual "... it is essential that local verification/calibration data be available at specific application sites to lend credibility to the predictions of any urban runoff model."

Calibration can be accomplished by first establishing stations so that flows can be measured at pertinent locations during rainfall events. Flow measurement can be accomplished with permanent gaging stations or with portable instruments. Ideally, continuous gaging stations should be established at each outfall location and at several locations within major outfalls such as Area 26 of the Beaver Brook drainage area. However, if manpower and funds are limited, it is desirable to at least gage several rainfall events at various locations to ensure adequate calibration of the SWMM.

As a minimum, peak flows should be measured during significant storm events at major outfall locations within each drainage area of the city. Some suggested outfalls at which peak flows should be measured include:

| Drainage Area | Outfall Number |
|---|---|
| Kendrick | 2 |
| Indian Lake | 3 |
| Coes Reservoir | 39 |
| Beaver Brook | 26 & 56 |
| Kettle | 65 |
| Middle River | 86 |
| Blackstone River | 93 |
| Broad Meadow Brook | 96 |
| Lake Quinsigamond | 110 |
| Mill Brook | 196 |

In addition, peak flow measurements should be made at outfalls with smaller catchment areas such as:

| Drainage Area | Outfall Number |
|---|---|
| Kendrick | 7 |
| Indian Lake | 19 |
| Coes Reservoir | 62 |
| Kettle | 82 |
| Broad Meadow Brook | 99 |
| Lake Quinsigamond | 128 |
| Mill Brook | 185 |

Peak flow measurements should also be made within some of the major outfalls, such as at Manhole #66 of Area 26, in the Beaver Brook drainage area. Greater accuracy can be achieved with numerous monitoring stations for several storm events than can be expected with limited data.

Infiltration should also be considered when calibrating the model. Infiltration into the pipe network was not modeled. According to the SWMM manual, "...Concurrent historical rainfall, water table, and sewer flow data of several weeks' duration are needed to completely describe infiltration." This effort was not within the scope of this study.

Measured pollutant concentrations at the outfalls are also required data for the calibration/verification process. Water quality predictions are not credible without adequate site-specific data for calibration and verification. Therefore, it is essential that water quality field data be obtained before attempting to use this model for pollutant concentration routing through that outfall's storm drain system.

Calibration of the model should be achieved using one set of storm data. Variables such as percent imperviousness, Manning's "n" values, and infiltration rates can be adjusted to calibrate the discharge peak flows. Depression storage has been excluded from the input because the City of Worcester is primarily hilly, providing very little depression storage. However, certain small sections of the city are relatively flat, therefore, calibration of the model may require depression storage values for these sites. It is recommended that this should be attempted only as a last means of calibration due to the difficulty associated with accurately accounting for these areas. Once the SWMM has been calibrated for one rainfall event, its ability to reproduce other rainfall events should be tested. Recorded rainfall data for other gaged events can be input to the model and the computed hydrographs can be compared to the observed hydrographs. If necessary, further adjustments to the parameters can be made to ensure accurate calibration.

Reference 3, "Efficacy of SWMM Application", describes the calibration and verification process used for a specific application of SWMM. The model in this reference was calibrated using a single storm event chosen from ten measured storm events. Nine storm events were then used to verify the predictive capabilities of this calibrated model.

Reference 3 looked at selection of calibration event, watershed conceptualization, and calibration parameter selection to determine which affected the calibration process the most. It found that "... There was a substantial impact of calibration storm event selection..". Field data from ten storm events were analyzed with the smallest event resulting in the worst overall performance of the model. Watershed conceptualization includes the physical characterization (width, ground slope) and number of subcatchments draining a particular outfall area. It was found that watershed conceptualization was not as significant as the impact of selecting a calibration storm event.

The SWMM manual states that there are sufficient parameters, particularly in the Runoff Block, which may be adjusted such that calibrating the model against measured data is readily accomplished. Reference 3 found that the use of percent imperviousness as the single model calibration parameter was substantially more successful than the adjustment of the pervious depression storage parameter. The determination of percent imperviousness can be accomplished with the aid of aerial photographs of the city.

Calibrating and verifying the SWMM is essential towards utilizing it as part of a comprehensive stormwater management plan within the City of Worcester. It is also essential for the eventual modeling of water quality constituents and pollutant loadings which may be required under the National Pollutant Discharge Elimination System permitting process.

# VI. SUMMARY

The process of modeling the Worcester storm drainage system utilized two major components of the SWMM application. These components are the Runoff Block and the Transport Block. Figure 2 illustrates the sequence of input, block applications, and output for this model.

The Runoff Block forms the source of runoff hydrographs for most other SWMM applications. The input data for this block is extremely important since it used within the Transport Block to generate the outfall hydrograph. The Runoff Block accepts a rainfall hyetograph; predicts runoff from the subcatchments on the basis of their individual characteristics, and determines the hydrographs at the inlets (subcatchments) to the drainage pipe network.

Routing stormwater flows through the pipe network is accomplished using the Transport Block. This block has been used only for routing of stormwater quantities, and did not involve routing of water quality parameters or estimating dry weather flow or infiltration.

The city was first divided into ten major drainage areas. The Beaver Brook Drainage Area was chosen to be used for a Pilot Study because it contains representative land use types and was complex enough to develop a methodology which could then be applied to the remaining drainage areas of the city. The outfalls and their respective pipe network boundaries were then identified using the Fay, Spofford, and Thorndike, Inc. storm drain maps. Each outfall was modeled separately and has its' own input file. Where an outfall is tributary to another outfall, the output hydrograph for the tributary area was input to the downstream outfall. This was accomplished using the Combine Block. Outfalls consisting of simple lines, small tributary areas, or combined sewer flows were not modeled.

A 25 Year rainfall event was used to model all of the outfall areas to reflect the city's design storm event for their drainage system. This 5.33 inch 25-Year 24-Hour rainfall total was developed from the U.S. Weather Bureau's Technical Publication (T.P.) No. 40 and was applied to a historic rainfall distribution based on the 31 March 1987 storm event. Figure 3 is the rainfall hyetograph for the 25 Year event.

A sensitivity analysis was also performed to determine the output's sensitivity to changes in certain parameters. Outfall hydrographs, and surface runoff from the subcatchments were compared for a range of values of a particular parameter. The sensitivity analysis concluded that minor variations in percent imperviousness (i.e., 20% instead of 25%) do not cause significant changes in the output, specifically the outfall hydrographs or surface runoff volume. However, more significant changes, such as increasing the percent imperviousness from 20% to 40%, or decreasing from 20% to 5% exhibit more pronounced changes in the volume of surface runoff and subsequently the outfall hydrographs. Therefore, it can be concluded that the results obtained from the application of this model are dependent on the accurate selection of percent imperviousness over the entire catchment area for an outfall area.

The SWMM is an extremely helpful tool for stormwater management. However, it is only as accurate as the data which is used as input. Due to limitations in the capabilities of the Transport Block, surcharging effects are not as accurately modeled as can be accomplished using the EXTRAN Block of the SWMM. EXTRAN has the ability to simulate pressure flow and surcharge, however it does not have the capabilities to model water quality. The decision to use the Transport Block instead of the EXTRAN Block was made at the start of this investigation by the City of Worcester. The Transport Block was chosen specifically so that the City of Worcester may use it to model water quality constituents and simulate pollutant load routing through the pipe network at some future date.

The model in its present form is uncalibrated and unverified. Steps to accomplish the calibration and verification of this model are required in order to successfully utilize it for more accurately predicting the rainfall runoff process along with producing pollutographs and modeling any combined sewers. Future work should include calibrating and verifying the existing model parameters and output. According to the SWMM manual "... it is essential that local verification/calibration data be available at specific application sites to lend credibility to the predictions of any urban runoff model."

Calibration can be accomplished by first establishing stations so that flows can be measured at pertinent locations during rainfall events. Flow measurement can be accomplished with permanent gaging stations or with portable instruments. Ideally, continuous gaging stations should be established at each outfall location and at several locations within major outfalls such as Area 26 of the Beaver Brook drainage area. However, if manpower and funds are limited, it is desirable to at least gage several rainfall events at various locations to ensure adequate calibration of the SWMM.

Measured pollutant concentrations at the outfalls are also required data for the calibration/verification process. Water quality predictions are not credible without adequate site-specific data for calibration and verification. Therefore, it is essential that water quality field data be obtained before attempting to use this model for pollutant concentration routing through that outfall's storm drain system.

Calibrating and verifying the SWMM is essential towards utilizing it as part of a comprehensive stormwater management plan within the City of Worcester. It is also essential for the eventual modeling of water quality constituents and pollutant loadings which may be required under the National Pollutant Discharge Elimination System permitting process.

## VII. ACKNOWLEDGMENTS

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This report was prepared under the supervision and management of the following New England Division personnel:

Colonel Philip R. Harris, Division Engineer
Joseph L. Ignazio, Director of Planning
John C. Craig, Chief, Basin Management Division
John R. Kennelly, Chief, Long Range Planning Branch

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# APPENDIX 1

## APPENDIX 1

A complete detailed description of the various input parameters is contained in the SWMM User's Manual. The following descriptions are presented only as a brief summary of the more significant parameters for this particular investigation. The input for the Runoff and Transport Blocks is briefly described below. The typical output of the SWMM is also briefly described.

### Input

A sample input data file for Outfall Area 3 also follows. Each line of the file is preceded by either a line identifier (A1, B2, etc.), or by an asterisk. The asterisk represents a comment or remarks line, and is not read as input in the model.

### Runoff Block

#### Input/Output

The Runoff Block accepts a rainfall hyetograph and makes a step by step accounting of infiltration losses in pervious areas, evaporation losses, and overland flow within each subcatchment. The output of this Block includes runoff hydrographs which are then routed through the stormwater pipe network using the Transport Block. (See "Transport Block", next section.) The Runoff Block also plots the rainfall hyetograph, total infiltration, the runoff hydrograph for a particular outfall drainage area, and calculates the continuity error.

Some of the important parameters required for input to this block are described below. All parameters are described in more detail in the SWMM manual.

#### Line B1: First Control Data Group

Parameters in this group are associated with choosing the type of infiltration equation, units, number of hyetographs, evaporation rate, and the starting time of the simulation.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| ISNOW | 0 | Snowmelt Not Simulated |
| NRGAG | 2 | Two rainfall events modeled. |
| INFILM | 0 | Horton Equation used. |
| IVAP | 0 | 0.1 inch/day. (Default value) |

#### Line B2: Second Control Data Group

Parameters for print control of the input/output.

Line B3: Third Control Data Group

Parameters of time steps associated with the simulation.

Line D1: First Rainfall Control Card

Precipitation input option.

Line E1: Second Rainfall Control Card

Parameters for precipitation input type, units, etc.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| KPREP | 0 | Precipitation Unit Type (In./Hr.) |
| NHISTO | 24 | Number of data points in hyetogr. |
| THISTO | 1 | Time interval. |

Line E3: Rainfall Input

Input values for desired rainfall hyetograph.

Line H1: Subcatchment Data

This input line contains parameters describing subcatchment characteristics, including width, percent imperviousness, slope, Manning's Roughness coefficients, depression storage, and infiltration for Horton's Equation.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| NAMEW | varies | Subcatchment numbers. These correspond to the inlet which receives the runoff. |
| NGTO | varies | Channel/pipe or manhole number. Corresponds to above subcatchment number. |
| WW1 | varies | Width of subcatchment (ft.). Refer to SWMM manual for details. |
| WW2 | " | Area of subcatchment (acres). |
| WW3 | " | Percent imperviousness. |
| WW4 | " | Slope. (ft./ft.) |
| WW5 | 0.014 | Manning's Roughness - Impervious |
| WW6 | 0.06 | Manning's Roughness - Pervious |
| WW7/WW8 | 0.0 | Depression storage constant. |
| WW9 | 0.5 | Max. infiltr. rate (in./hr.) |
| WW10 | 0.1 | Min. " " " |
| WW11 | 0.0001 | Decay rate of infiltr. (1/sec.) The infiltr. parameters are constant for all subcatchments. |

## Transport Block

### Input/Output

The input needed for the Transport Block characterizes the physical dimensions of the stormwater network which is to be modeled. This includes pipe dimensions, roughness factors, and slopes. Infiltration of the system was not included in this model. The output of the Transport Block consists of a final surcharging summary table, and output hydrographs at the outfalls or other desired points along the pipe network.

### Line B1: First Control Data Group

Parameters in this group identify elements and hydrographs to be printed or transferred to other blocks, and units of measurement.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| NINPUT | 0 | No input of other hydrographs. |
| NNYN | varies | # of non-conduit elements at which input hydrographs are to be printed out. |
| NNPE | varies | # of non-conduit elements at which routed hydrographs are to be printed out. |
| NOUTS | varies | # of non-conduit elements at which flow is to be transferred to the Graph Block for subsequent plotting. |
| NITER | 4 | Recommended # of iterations in SWMM manual. |

### Line B2: Second Control Data Group

Identifies parameters such as allowable error of convergence, total area of catchment, and kinematic viscosity of water.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| EPSIL | 0.0001 | Recommended allowable error. |
| GNU | 0.00001 | Kinematic viscosity of water. |
| TRIBA | varies | Total area of outfall. (acres) |

Line B3: Third Control Data Group

Identifies inlet hydrographs to be transferred from previous block (NCNTRL), and parameters for infiltration and dry-weather flow. Infiltration and dry-weather flow were not modeled.

Line E1: Sewer Element Data

Parameters which describe physical characteristics of pipe elements to be modeled.

| PARAMETER | VALUE | REMARKS |
|---|---|---|
| NOE | varies | Element number. |
| NUE(1) | varies | Upstream element numbers. |
| NUE(2) | " | " " " |
| NUE(3) | " | " " " |
| NTYPE | varies | Element type. |
| DIST | " | Conduit length (ft.). |
| GEOM1 | " | See Manual Fig. 6-3; Table 6-3 |
| SLOPE | " | Slope of conduit (ft./100 ft.). |
| ROUGH | 0.014 | Manning's Roughness (Constant) |
| GEOM2 | varies | See Manual Fig.6-3; Table 6-3 |

Line H1: List of external non-conduit elements at which hydrographs are to be transferred to subsequent blocks. The number of hydrographs requested here must equal parameter NOUTS. Any hydrographs to be plotted in the Graph Block must be listed on this line.

Line J1: List of external non-conduit elements at which input hydrographs are to be stored and printed. These elements are those that receive runoff flow from the subcatchments. The number of elements listed here must equal parameter NNYN.

Line J2: List of external non-conduit elements that the user desires routed hydrographs at. The number of elements listed here must equal parameter NNPE.

Output

The typical SWMM output file reflects the input data provided by the user and provides various forms of output relating to the generation of selected hydrographs. The following is a list of some of the more significant output in a typical output file:

- Summarizes parameters of the Runoff Block.
- Summarizes rainfall and subcatchment data.
- Provides a continuity check of surface water which includes:
  - precipitation
  - infiltration
  - evaporation
  - surface runoff
  - surface storage
  - infiltration
- Calculates the error in continuity.

  Provides continuity check for subcatchment.
- Prints rainfall hyetograph.
- Prints surface inlet hydrograph flow summation for all inlets.
- Provides a printout of the infiltration rate over the desired time period.

Upon completion of the Runoff simulation, the Transport Block is then entered. This section of the output contains:

- Summaries of the input parameters.
- Summaries of the element data and SWMM computation sequence.
- Summary of the transport element parameters.
- Summary of element flows initialized to dry weather and infiltration flows. This is zero for all elements of this study since dry weather flow and infiltration are not accounted for.
- A summary of the Transport Block flow continuity and error.
- A summary of surcharged elements including location and duration.
- The total flow through non-conduit elements (manholes).
- Output hydrographs at selected elements.

```
*SWMM MODEL DATA FOR AREA 3  -- WORCESTER
*PIPES 30 IN. AND OVER -- COARSE DISCRETIZATION
*  NBLOCK  JIN(1)  JOUT(1)  JIN (2)  JOUT(2)  JIN(3)  JOUT(3)
SW   3       0        9        9        10       10       41
*  SCRATCH FILES
MM   6  11 12 13 14 15 16
* SAVED FILES FOR GRAPHING
*PRINT CONTROL PARAMETERS
@ 10 'AREA  3T.INT'
*
$RUNOFF
A1 'WORCESTER SWMM MODEL'
A1 'DRAINAGE AREA 3  '
*  METRIC ISNOW NRGAG INFILM KWALTY IVAP NHR NMN NDAY MONTH IYRSTR
B1    0     0     1     0     0     0    0   0   31    3     87
*  IPRN(1)    IPRN(2)    IPRN(3)
B2   0          0          0
*  30 MIN TIME STEP, 24 HOUR SIMULATION
*     WET     WETDRY      DRY      LUNIT      LONG
B3    1800    3600      86400        2         24
*RAINFALL CONTROL
D1 0
* KTYPE KINC KPRINT KTHIS KTIME KPREP NHISTO THISTO TZRAIN
E1  0    24     1     0     1     0    24     1      0.0
* STEP FUNCTION HYETOGRAPH -- 25 YEAR STORM
E3  0.00 0.05 0.08 0.07 0.14 0.29 0.47 0.19 0.23 0.12 0.23 0.32 0.34
    0.53 0.26 0.12 0.35 0.33 0.29 0.35 0.19 0.16 0.13 0.09
*DRAINAGE AREA--SUBCATCHMENTS
*            MANHL  WDTH AREA %IMP SLOPE IMP   PER               INFILTRA   DECAY
*             NUM    ft   acre       ft/ft MAN   MAN   storage   MAX  MIN
*  JK  NAMEW NGTO  WW1   WW2  WW3   WW4   WW5   WW6  WW7  WW8   WW9  WW10  WW11
H1  1    2     2  2940  332.3  10 0.061 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   12    12  2680   10.1  20 0.013 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   20    20  1240    6.2  10 0.029 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   24    24  1160    4.8  10 0.033 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   30    30 13440  247.4  25 0.027 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   40    40  7380   53.1  25 0.025 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   48    48  5120   42.1  30 0.031 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   56    56  1280    3.8  20 0.015 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
H1  1   58    58   460   13.6  20 0.028 0.014 0.06 0.0  0.0   0.5  0.10 0.0001
*PRINT CONTROL PARAMETERS
*  NPRNT   INTERV
M1   0        0
*IF NPRNT = 0 ON LINE M1 SKIP GROUPS M2 AND M3
*   NDET   STARTP(1)  STOPPR(1) ... STARTP(NDET)  STOPPR(NDET)
*M2  1         0          0
*CHANNEL/INLET PRINTOUT LOCATIONS
*   IPRNT(1)    IPRNT(2)   ...   IPRNT(NRPNT)
*M3
*
```

RUNOFF BLOCK

```
*TRANSPORT BLOCK DATA
$TRANSPORT
A1 'DRAINAGE AREA 3 '
A1 ' '
*  NDT  NINPUT  NNYN  NNPE  NOUTS  NPRINT  NPOLL  NITER  IDATEZ  METRIC  INTPRT
B1  48    0       1     1     1       0       0      4    870331     0       0
*   DT    EPSIL     DWDAYS    TZERO    GNU      TRIBA
B2 1800  0.0001       7        0.0   0.00001   713.4
*   NCNTRL     NINFIL    NFILTH    NDESN
B3    0           0         0         0
```

TRANSPORT BLOCK

```
*     NKLASS     KPRINT
C1       0          0
* PIPE DATA
*ELEMENT        UPSTREAM           ELE  LENGTH DIM           MAN    DIM
*  NUM      ELEMENT NUMBERS        TYPE   ft    ft   ft/100   N     ft
*  NOE    NUE(1) NUE(2) NUE(3) NTYPE DIST GEOM1 SLOPE ROUGH GEOM2 BARREL GEOM3
E1   1000    1      0      0     19     0     0      0     0      0      0     0
E1      1    2      0      0     1     59.0   2    1.79  0.014    0      0     0
E1      2    3      0      0     19     0     0     0      0      0      0     0
E1      3   12      0      0     1    764.7   2    1.79  0.014    0      0     0
E1     12   13      0      0     19     0     0      0     0      0      0     0
E1     13   14      0      0     1    243.5  1.5   3.15  0.014    0      0     0
E1     14   15      0      0     19     0     0      0     0      0      0     0
E1     15   20      0      0     1    475    1.25 5.04  0.014    0      0     0
E1     20   21      0      0     19     0     0      0     0      0      0     0
E1     21   24      0      0     1    353.3  1     5.3   0.014    0      0     0
E1     24   25      0      0     19     0     0      0     0      0      0     0
E1     25   30      0      0     1    334.3  2     5.28  0.014    0      0     0
E1     30   31      0      0     19     0     0      0     0      0      0     0
E1     31   40      0      0     1    930.5  1.75 5.42  0.014    0      0     0
E1     40   41      0      0     19     0     0      0     0      0      0     0
E1     41   48      0      0     1    912.1  1.5  5.31  0.014    0      0     0
E1     48   49      0      0     19     0     0      0     0      0      0     0
E1     49   56      0      0     1    971.1  1.5  4.27  0.014    0      0     0
E1     56   57      0      0     19     0     0      0     0      0      0     0
E1     57   58      0      0     1    331.9  1.25  4.14 0.014    0      0     0
E1     58    0      0      0     19     0     0      0     0      0      0     0
*LIST OF EXTERNAL NON-CONDUIT ELEMENTS PRINTED TO INTERFACE FILE
H1  1000
*LIST OF NON-CONDUIT ELEMENTS FOR WHICH INPUT HYDROGRAPHS ARE TO BE PRINTED
J1  58
*LIST OF EXTERNAL NON-CONDUIT ELEMENTS FOR OUTPUT HYDROGRAPHS
J2  1000
$GRAPH
*    NTAPE    NPLOT    MEAS    MFILE    MPLOT    NQP    METRIC    MCTH
A1    10        1       0        0        0       0       0         0
C1   1000
D1    ' AREA  3  - OUTPUT HYDROGRAPHS'
$ENDPROGRAM
```

TRANSPORT BLOCK

GRAPH BLOCK

Listed below are the input and output file names for SWMM for each of the drainage areas. These files have been compressed using a program called "PKZIP". This program shrinks large files down to a more manageable size for storage purposes. All of the data and output files associated with each of the ten drainage areas has been "zipped" down. These files can be easily restored to their original size using the "PKUNZIP" command.

| "ZIPPED" FILE NAME | INPUT/OUTPUT FILE NAMES | COMMENTS |
|---|---|---|
| BEAVDAT.ZIP | BEAV.DAT | Input data files for Beaver Brook. |
| BEAVOUT.ZIP | BEAV.OUT | Output files from SWMM. |
| BLCKDAT.ZIP | BLCK.DAT | Input data files for Blackstone River. |
| BLCKOUT.ZIP | BLCK.OUT | Output files from SWMM. |
| BRBKDAT.ZIP | BRBK.DAT | Input data files for Broad Meadow Brook. |
| BRBKOUT.ZIP | BRBK.OUT | Output files from SWMM. |
| COESDAT.ZIP | COES.DAT | Input data files for Coes Reservoir. |
| COESOUT.ZIP | COES.OUT | Output files from SWMM. |
| INDLKDAT.ZIP | INDLK.DAT | Input data files for Indian Lake. |
| INDLKOUT.ZIP | INDLK.OUT | Output files from SWMM. |
| KENDDAT.ZIP | KEND.DAT | Input data files for Kendrick. |
| KENDOUT.ZIP | KEND.OUT | Output files from SWMM. |
| KETTDAT.ZIP | KETT.DAT | Input data files for Kettle Brook. |
| KETTOUT.ZIP | KETT.OUT | Output files from SWMM. |
| MIDDDAT.ZIP | MIDD.DAT | Input data files for Middle River. |
| MIDDOUT.ZIP | MIDD.OUT | Output files from SWMM. |
| MILLDAT.ZIP | MILL.DAT | Input data files for Mill Brook. |
| MILLOUT.ZIP | MILL.OUT | Output files from SWMM. |
| QUINDAT.ZIP | QUIN.DAT | Input data files for Lake Quinsigamond. |
| QUINOUT.ZIP | QUIN.OUT | Output files from SWMM. |

Listed below are the AutoCad (ACAD) drawing files used in this study.

| DRAWING FILE | COMMENTS |
|---|---|
| WORC1.DWG | Master drawing containing all outfall boundaries, pipe networks, etc. All other drawings were created from this drawing file. |
| MIDD.DWG | Middle River Drainage Area. |
| MILLBK.DWG | Mill Brook Drainage Area. |
| BLACK.DWG | Blackstone River Drainage Area. |
| KEND.DWG | Kendrick Drainage Area. |
| KETTLE.DWG | Kettle Brook Drainage Area. |
| BEAVER.DWG | Beaver Brook Drainage Area. |
| BROAD.DWG | Broad Meadow Brook Drainage Area. |
| INDIAN.DWG | Indian River Drainage Area. |
| COES.DWG | Coes Reservoir Drainage Area. |
| QUIN.DWG | North portion of Lake Quinsigamond Drainage Area. |
| QUINS.DWG | South portion of Lake Quinsigamond Drainage Area. |

ACAD allows the user to save "views" of certain portions of a particularly large drawing such as WORC1.DWG. These "views" may be called up using the VIEW command in ACAD. The views contained in the WORC1.DWG file are:

1. ALL - Provides an overall view of the entire city.
2. INDIAN - Indian Lake Drainage Area.
3. KENDRICK - Kendrick Drainage Area.
4. BEAVER - Beaver Brook Drainage Area.
5. LAKEQ - Lake Quinsigamond Drainage Area.
6. BROAD - Broad Meadow Brook Drainage Area.
7. BLACK - Blackstone River Drainage Area.
8. MILLBK - Mill Brook Drainage Area.
9. MIDDLE - Middle River Drainage Area.
10. COES - South portion of Coes Reservoir Drainage Area.
11. COESEXT - North portion of Coes Reservoir Drainage Area.

AutoCad Layers
WORC1.DWG

| LAYER | COMMENTS |
|---|---|
| 0 | Contains boundaries of city limits. |
| RAIL | Rail lines. |
| TEXT | Street/River names. |
| STREETS | Graphic representation of the streets. |
| RIVERS | Watercourses and rivers. |
| TITLE | Scale and Title block. |
| ---_OUT | Outfall boundaries. |
| ---_TEXT | Outfall ID numbers. |
| ---_PIPES | Outfall pipe/manhole schematic representation. |
| DRAIN | Drainage Area boundaries. |
| DRAIN_TEXT | Drainage Area names. |
| OUT_LOCATIONS | Approximate location of outfalls. |

APPENDIX 2

## APPENDIX 2

## REFERENCES


1. Storm Water Management Model, Version 4: User's Manual August 1988, Wayne C. Huber and Robert E. Dickinson

2. Topographical Maps - Moore Survey & Mapping Corporation, 1975

3. "Efficacy of SWMM Application", J. J. Warwick and P. Tadepalli, June 1990. Journal of Water Resources Planning and Management, Vol. 117, No.3, May/June 1991.

4. Technical Paper Number 40 (T.P. 40) - U.S. Weather Bureau.

5. Manual of Engineering Practice, Number 28 - American Society of Civil Engineers (ASCE).